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RESEARCH ON THE INFLUENCE OF CONDITIONS OF FLOW, SUBCOOLING AND COMPOSITION ON THE BURNOUT HEAT FLUX OF POLYPHENYL REACTOR COOLING AGENTS

by

D. A. van MEEL and M. L. G. van GASSELT
(TNO)

1966

ORGEL Program

Report prepared by
the Central Technical Institute TNO, Rijswijk — Netherlands

Euratom Contract No. 166-64-6 ORGN

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Recommended correlations are presented for heat transfer and pressure drop, for upflow through the round 5 mm vertical tube, 500 mm in length.

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Summary

Research carried out by the Central Technical Institute TNO Holland from June 1, 1964 under contract No. 166-64-6 ORGN with Euratom on forced convection non-boiling, subcooled boiling- and subcooled burn-out heat transfer and pressure drop of terphenyl mixtures in vertical test sections is summarized.

Recommended correlations are presented for heat transfer and pressure drop, for upflow through the round 5 mm vertical tube, 500 m in length.

CONTENTS

I. INTRODUCTION

In 1961 investigations started at the Central Technical Institute TNO on the burn-out heat flux of mixtures of terphenyls.

The work was part of the Euratom programme on the "Orgel" organic-cooled, heavy water moderated power reactor.

Under contract 019-61 Org H with Euratom, the test facilities had been provided and a large number of measurements made on liquids OM2 and OM1 pressurized directly by nitrogen as a cover-gas.

In June 1963 the work was continued for a period of one year under contract 097-63-6 Org N. The primary objective of continuation was to obtain information on the effect of small concentrations of low-boiling components on the critical heat flux. Because of their volatility these components considerably reduce the degree of subcooling existing at a given pressure, and may have a deleterious effect on the critical heat flux. In support of this study apparatus for measurement of vapour pressure was devised.

In June 1964 the work was continued for another period of a year and a half under contract 166-64-6 Org N. During this period further information has been obtained on the effect of small concentrations of benzene, diphenyl, nitrogen, methane and high-boiling components on the critical heat flux in a vertical, 5.04 mm inside diameter, round stainless steel tube. In addition, the influence of non-circular cross-sectional geometries of vertical tubes on the critical heat flux has been studied for degassed OM2.

Finally, forced convection non-boiling- and subcooled boiling heat transfer and pressure drop have been studied for degassed OM2 in a vertical, 4.94 mm inside diameter, round stainless steel tube.

The results of earlier TNO experiments in a vertical tube are described in Ref. 1. At that time no satisfactory means were available of controlling the degree of pyrolysis of the coolant, such as saturation pressure measurements made at a later stage of the investigations, which were very effective in this respect. Part of these early results probably relate to inadequately defined coolant compositions and may now be considered as preliminary.

In this report a general description of the final experimental set-up is given and the more important final results obtained for the system studied are summarized and correlated.

Manuscript received on June 6, 1966.

II. APPARATUS

A. The test loop

The loop is constructed from stainless steel 316 for a maximum pressure of 30 bar at a temperature of 450°C. A schematic diagram of the loop as used in the experiments now reviewed is presented in Fig. 1.

The loop is completely filled with about 30 litres of liquid. It contains a vessel in which a diving bell floats on molten solder, allowing thermal expansion of the liquid by 30%. The solder separates the liquid from the nitrogen used to pressurize the liquid. The liquid is pumped from a suction vessel into the circuit, flows through a sintered stainless steel filter, a turbine flowmeter and the test section and may return to the suction vessel via a cooler or via a by-pass if cooling is not required. To provide hydrodynamic equilibrium at the inlet of the test tube, a straight piece of tube 50 cm in length and of the same inner diameter as the test tube is inserted between the flowmeter and the test tube inlet. The loop may be filled by sucking the terphenyl from the storage vessel after evacuating the circuit.

The entire circuit is provided with Pyrotenax trace-heating cable and is thermally insulated with expanded mica. For reasons of safety the loop is enclosed in a reinforced brick cabin and is operated from outside.

The pump was specially constructed by the Central Technical Institute TNO. It consists of a modified single-stage regenerative pump (make Sihi) provided with a mechanical seal (make Flexibox), which is cooled by a thermo-syphon system containing water. The pump capacity is 800 l/h at a pressure head of 5 atm and 3000 r.p.m. The heat exchanger is of the tube-in-tube type. The cooling agent is water. The valves used in the liquid ducts are of the bellows-seal type.

The apparatus for measurement of vapour pressures at temperatures up to 450°C and pressures up to 30 bar was specially constructed by CTI-TNO (Ref. 2) and is connected in parallel with the circuit.

B. The test section

A simplified diagram of the test section is given in Fig. 2. Its essential part is the thin-walled test tube made of stainless steel 316, heated by means of the Joule effect using direct current.

The dimensions of the test tube are: heated length 500 mm, inner diameter 5 mm, wall thickness 0.25 mm. Pieces of tubes having a relative wall-thickness variation of less than 5% were selected from commercial tubing using X-ray wall-thickness measurements. The test tube is enclosed in a pressure chamber having the same pressure as in the test tube. To prevent the tube from deforming by thermal expansion, it is pre-stressed at room temperature, so that it will be practically unstressed when heated.

An unheated length of 500 mm, 5 mm-bore tube precedes the test tube. A bellows is inserted as a flexible element in the unheated upper part of the test section. The upper part of the test tube is electrically separated from the earthed parts of the loop by using insulating packing materials between flanges and bolts.

III. INSTRUMENTATION

A. Burn-out detection

The test tube is prevented from damage by means of a burn-out detector actuating a high-speed switch which cuts off the current through the test tube when development of a hot spot is detected. The high-speed switch was made by Smit (Slikkerveer).

The test tube has electrical connections at the ends and in the middle, dividing it into two resistances which form part of a Wheatstone bridge. If there is a steep local increase in the wall temperature in the upper part of the test tube owing to a transition to film-boiling, a diagonal voltage occurs across the bridge. This voltage is amplified and used to operate a thyratron relay tube; this closes a circuit which incorporates the cut-out relay of the high-speed switch. A differentiating circuit is included in the system to ensure that the burn-out detector reacts only to quick-changing signals.

A more detailed description of the circuit of the burn-out detector, which was constructed by the Institute TNO for Mechanical Constructions, is given in Ref. 3.

The total switching time of 0.014 sec and the sensitivity of the burn-out detector proved to be sufficient to protect the test tube under the severest conditions.

B. Temperature measurement

Temperatures are recorded at various locations in the test loop (Fig. 1).

The most important are the temperatures of the liquid at the entrance and exit of the test tube. These are measured by fast-responding bare Ni-NiCr thermocouples which have been aged and are calibrated within 0.5°C.

Inlet and outlet temperatures are recorded simultaneously on a double-line recorder. The outlet temperature, which is of primary importance since it is used for calculating the degree of subcooling, is measured close to the test tube outlet as indicated in Fig. 2. The inlet and outlet temperature measurements of the test tube are accurate to 0.5°C.

The outside wall temperature of the test tube is measured with a "Thermodot" radiation pyrometer, model TD-6B (response time 300 msec) (see Fig. 2).

The test section has a rectangular flange over its entire length in which 14 barrels about 7 cm in length are screwed. A quartz sight-glass (14 mm diameter, 4 mm thick) is fixed at the end of each barrel. The ends of the barrels are surrounded by Pyrotenax wire in order to heat the glasses to about 200°C to prevent condensation of terphenyl vapours. The test section is kept at a temperature of about 150°C for the same reason. The quartz glasses are about 5 mm from the wall of the test tube. The pyrometer observes the outside surface of the test tube through the quartz sight-glasses.

The pyrometer is screwed to a water-cooled base fixed on the swivel-base mount of an elevator column. It is positioned about 51 cm from the test tube and can be moved up and down. The target is 3.5 mm in diameter. The optics are so constructed that when the target is visually in focus, the infra-red image is also focused on the detector. The elevator column is adjusted with an electric motor and reducing gear. A revolution counter connected to the motor by a flexible shaft indicates the height of the radiometer relative to the test tube.

The surface of the test tube was sprayed black with an alcoholic solution of colloidal graphite, Aquadag brand, so that the test tube would have a constant coefficient of emission along its entire length.

The pyrometer was calibrated up to 600°C and checked against the outside wall temperature of the non-heated test tube, which equals the outlet temperature of the fluid under steady-state conditions.

If the heat loss of the test tube by radiation (<1%) is disregarded, the wet-wall temperature can be calculated with the following formula

$$t_{w,w} = t_{w,d} - \frac{\Phi\, d}{2\,\lambda}$$

$t_{w,w}$ = inside wall temperature of the test tube, in °C
$t_{w,d}$ = outside wall temperature of the test tube, in °C
Φ = heat flux in W/cm^2, for upper 10 cm of test tube
λ = thermal conductivity of the test tube material at about 450°C, in W/m°C

d = wall thickness of the test tube, in m

The wet-wall temperature measurements of the test tube are accurate to about $\pm$ 2°C.

C. Pressure

The static pressure at the outlet of the test tube used for calculating the degree of subcooling is recorded continuously by means of a Barton differential-pressure cell accurate to 1%.

The pressure-drop measurements across the test tube are also recorded continuously with two separate Barton differential-pressure cells accurate to 2%.

The trace-heated pressure leads are connected direct to the pressure measuring cells.

The Barton unit as a whole is heated electrically to 100°C to keep the terphenyl molten.

D. Flow

A continuously recording turbine flowmeter is used to measure the volumetric flow rate.

Calibration with water at different levels of temperature using the weighing method showed that the flow resistance of the unheated test tube obeys Blasius' law; an additional flow measurement procedure was therefore adopted, consisting of measurement of the isothermal pressure drop across the unheated test tube.

The flow measurement is accurate to 1%.

E. Power

The DC current (max. 30 kW) through the test tube and the voltage drop across the test tube are measured with recording instruments. Furthermore, the voltage drop across the upper 10 cm of the test tube, in which region burn-out occurs, is recorded in order to obtain a closer approximation to the local value of the burn-out heat flux.

The electrical energy input as calculated by multiplication of current and voltage drop is accurate to about 3%. Its accuracy decreases for small heat inputs (<100 W/cm^2).

IV. TEST PROCEDURE AND HEAT BALANCE

The procedure for making burn-out measurements is as follows. First the desired pressure level is adjusted. Next a certain liquid velocity is adjusted. Then the voltage is raised at a constant rate until the critical heat flux is reached.

The heat input into the test tube increases the temperature of the liquid, decreasing the degree of subcooling. By this means a series of burn-out heat fluxes is obtained at constant liquid velocity and constant pressure as a function of the degree of subcooling. At the end of a series, the liquid is cooled with the water-cooled heat exchanger; another velocity is chosen and the cycle starts again.

Actually, for the flow circuit and the pump as used, both liquid velocity and static pressure at the test tube outlet vary as a function of heat input into the test tube. The moment very tiny bubbles of vapour start to form on the wall of the test tube there is a small decrease in velocity because of the increasing resistance to flow. For the purpose of correlation, the values of the liquid flow-rate and the static pressure at the tube outlet as recorded at the moment of burn-out were used.

The procedure for making non-boiling and subcooled boiling heat transfer tests is as follows. An adjustable contact was introduced into the double-line recorder of the inlet and outlet temperature, making it possible to actuate the burn-out detector at a certain pre-determined outlet temperature. At constant static pressure the degree of subcooling at the outlet of the tube is accordingly also kept constant. The desired pressure level and mass velocity of the liquid are adjusted and kept constant. The pyrometer is directed to the upper quartz view-glass of the test section, situated about 4 mm from the top of the test tube. Next, the voltage across the tube is raised at a constant rate until the preset outlet temperature is reached. The contact then actuates the burn-out detector, and the power is switched off. The pyrometer records the outside wall temperature continuously. This procedure may be repeated for the quartz glasses that follow, keeping the inlet temperature constant, each time adjusting the radiation pyrometer to a lower glass, until the whole temperature profile along the test tube has been measured.

The inlet temperature of the liquid is then increased a little and the measurements started again at the upper quartz glass.

In this way a series of boiling heat fluxes with corresponding outside wall temperatures is obtained at constant mass velocity, constant pressure and constant degree of subcooling as a function of the inlet temperature.

The entire procedure can then be repeated for a different mass velocity and degree of subcooling, until a certain subcooled boiling regime for forced convection has been explored.

Comparison of the electrical heat input and the increase in the heat content of the liquid shows that the total heat loss of the test tube is about 3%. This agrees with estimates of conduction and radiation losses found by calculation. Most of the heat losses are to the lower end flange of the test section. Since only the upper 10 cm is used for measurement of the electrical heat input, no corrections are made as in that part heat losses may be disregarded.

V. PHYSICAL PROPERTIES

A. Composition of mixtures of terphenyl isomers

The mixtures of terphenyl isomers are manufactured by Progil (France).

The liquid to be used in Orgel is indicated as OM2. Its composition is: diphenyl <1 wt.%, o-terphenyl 14-16 wt.%, m-terphenyl 79-81 wt.%, p-terphenyl 3-5 wt.%, according to Progil's pamphlet.

B. Density, viscosity etc.

The data for density, viscosity, specific heat, heat of vaporisation, Prandtl number and thermal conductivity were obtained from Euratom (Ref. 5).

C. Saturation temperatures

The saturation temperatures of the terphenyl mixtures with low- and high-boiler components were measured with the aid of the TNO vapour pressure apparatus (Ref. 2).

OM2

The vapour pressure curve for OM2 is given in Fig. 3.

OM2-benzene system

Fig. 3 gives results of measurements with OM2 containing 0.2, 0.5, 1 and 1.5 wt.% benzene. Attention is drawn to the fact that a linear relation is obtained when this graph is used to plot pressure in relation to benzene concentration at constant temperature.

OM2-diphenyl system

The results of the measurements with OM2 containing 3, 6 and 9 wt.% diphenyl are given in Fig. 4. Regarding OM2 as one component and diphenyl as the other component of a binary system it can be concluded that Raoult's law can be applied.

OM2 with 0.023 wt.% nitrogen

The vapour pressure curve for this system is given in Fig. 5.

OM2 with 0.025 wt.% methane

The vapour pressure curve for this mixture is also given in Fig. 5.

OM2 with 15 wt.% high-boilers

The high-boilers used in this study are formed radiolytically and were provided by Euratom, Ispra. Although this mixture did not possess much thermal stability, the vapour pressure was measured and is shown in Fig. 5.

"Orgel cooling liquid" imitation

Its composition, as determined for the less volatile components by the Central Laboratory TNO, was roughly as follows:

16	wt.% high-boilers
0.5	wt.% phenantrene and triphenylene
20	wt.% ortho-terphenyl
56	wt.% meta-terphenyl
4	wt.% para-terphenyl
3	wt.% diphenyl
0.3	wt.% benzene
0.1	wt.% low-boilers
0.005	wt.% nitrogen, methane, hydrogen

The vapour pressure curve of this mixtures is given in Fig. 5

The vapour pressure measurements are estimated to be accurate to 0.5%.

The density of the mixtures of OM2 with low- and high-boiling components has been corrected for these additives. The changes in viscosity, specific heat, thermal conductivity etc. of OM2 due to the small concentrations of low- and high-boiling components and gases have been disregarded, since these properties do not occur in the burn-out correlations as far as they are developed here.

VI. RESULTS AND DISCUSSION

A. General

During the course of the investigation some intentional physical burn-out tests demonstrated that the heat flux at which the detector cuts off the heating current may be considered to be equal to the burn-out heat flux.

The degree of subcooling (Δt_{sub}) is defined as the difference between the saturation temperature of the fluid at the static pressure at the test tube outlet and the outlet bulk temperature of the liquid.

In most of the runs in which the test tubes were subjected to a physical burn-out, the failure was located near the exit about 5 mm from the top.

The long-term reproducibility of the burn-out measurements is generally about 3%. This confirms earlier observations indicating that fouling conditions have a negligible influence under the prevalent experimental conditions.

B. Forced convection subcooled burn-out heat transfer

1. Investigations effected for upward flow in the vertical, 5 mm inner diameter, round stainless steel tube

a. OM2 pure

Burn-out

It is emphasized that for the burn-out experiments with terphenyls the variables were evaluated at the outlet of the test tube, i.e. for conditions very close to those at the location of the burn-out.

About 70 runs were made with four different loads of the loop with pure degassed OM2 at a static outlet pressure of 2.9 bar. Figure 6 shows the results.

Correlation of the burn-out heat flux $\Phi_{b.o.}$ as obtained from the electrical heat input for the upper 10 cm of the test tube with the degree of subcooling at the outlet of the test tube $\Delta t_{sub_{OM2}}$ and the mass-velocity φ_m was determined graphically.

The equation found was

$$\Phi_{b.o.} = 125 + 27.6\ \varphi_m\ \Delta t_{sub_{OM2}} \qquad (1)$$

valid for the following conditions:
static pressure at outlet test tube 2.9 bar
mass-velocity φ_m from 0.065 to 0.20 kg/sec
degree of outlet subcooling $\Delta t_{sub_{OM2}}$ 20° - 90°C
test tube, length 500 mm
inner diameter 5.04 mm
wall thickness 0.25 mm
smooth drawn commercial tube, cleaned with "Vim"
upward flow.

The average scatter of the data is within 4%.

The simple engineering correlations of the burn-out heat flux data given in this report are satisfactory for the indicated limited ranges of subcooling and velocity

During the three years' investigation it appeared that other forms of equation are necessary for an acceptable correlation for wider ranges of variables.

This is demonstrated in Fig. 7, where two velocities are shown for which the burn-out heat flux is measured down to small degrees of subcooling. The figure shows that in this case curved lines are to be preferred to straight lines to connect the points of measurement.

It also appears that the linear relation observed earlier between the burn-out heat flux and the degree of subcooling is not valid for a wide range of subcoolings. This is the reason why the given simple correlations are preferred to the more complicated formulae given formerly, which were also based on this linear relation.

The vapour pressure of all the fresh OM2 loads used during the period of this contract remained within 3% of the curve given in Fig. 3. Otherwise the load was discarded.

The burn-out heat flux also depends to some extent on the inlet conditions and the damping and resonance character-

istics of the loop, and therefore on the arrangement of the throttling points and the main reservoir of the test rig. This follows also from Russian and American studies of burn-out.

In the course of this research the loop was modified several times, in that pump characteristics, flow adjustments and burn-out detection were improved.

For this reason, the burn-out heat fluxes measured after these modifications are higher than the results obtained formerly. No special study of the effect of pump characteristics has been made, however.

At the location of burn-out a very thin black layer is deposited on the inner tube surface. In a case in which about 400 "burn-outs" were produced in one and the same tube it could not be detected that changing surface conditions had any effect on the burn-out heat flux. However, no special attention could be paid to this.

Pressure drop

The pressure drop across the 500 mm heated test tube at burn-out can be calculated from the following friction factor correlation, which will be discussed below

$$f_h = 0.0105 + 10^{-4} (\Phi + 24) \tan\left(99.26\, e^{-11.16\, \varphi_m - 5.255\, 10^{-3}\, \Delta t_{sub}}\right) \quad (2)$$

This equation is used in conjunction with the frictional pressure drop correlation

$$\Delta p = f_h \frac{8\, L\, \varphi_m^2}{\pi^2\, D^5\, \rho} \quad (3)$$

with ρ evaluated at the average bulk temperature across the test tube.

Calculation of the friction factor f_h is accurate to about 4%.

b. OM2-benzene system

Pure benzene was distilled and the fraction at 80.4°C at 764.4 mm Hg was used for these experiments.

Burn-out

The burn-out heat flux of OM2 with 0.5 wt.% benzene was correlated by

$$\Phi_{b.o.} = 115 + 33.4\ \varphi_m\ (\Delta t_{sub_{OM2}} - 17.4) \qquad (4)$$

in which

$$\Delta t_{sub_{OM2}} = t_{sat_{pure\ OM2}} - t_{bulk_{outlet}}$$

or by

$$\Phi_{b.o.} = 115 + 33.4\ \varphi_m\ (\Delta t_{sub_{mix}} + 4.7) \qquad (4a)$$

in which

$$\Delta t_{sub_{mix}} = t_{sat_{mix}} - t_{bulk_{outlet}}$$

For a mixture of OM2 with 1 wt.% benzene the same type of correlation was made

$$\Phi_{b.o.} = 96 + 37.6\ \varphi_m\ (\Delta t_{sub_{OM2}} - 5.6) \qquad (5)$$

and

$$\Phi_{b.o.} = 96 + 37.6\ \varphi_m\ (\Delta t_{sub_{mix}} + 16.5) \qquad (5a)$$

The data lie within 4% of the given correlations.

An intentional physical burn-out with OM2 with 1 wt.% benzene had a heat flux 4% higher than that found in the test runs as measured by the actuation of the burn-out detector and represented by the correlation given above.

Pressure drop

Burn-out pressure drops for these systems were not measured.

c. OM2-diphenyl systems

The diphenyl used in the investigation was a technical grade supplied by Bayer A.G., Leverkusen, Germany.

Burn-out

The burn-out heat flux of OM2 with 6 wt.% diphenyl was correlated by

$$\Phi_{b.o.} = 110 + 34\ \varphi_m\ (\Delta t_{sub_{OM2}} - 16.3) \qquad (6)$$

or

$$\Phi_{b.o.} = 110 + 34\ \varphi_m\ \Delta t_{sub_{mix}} \qquad (6a)$$

For the 9 wt.% diphenyl mixture the correlation becomes

$$\Phi_{b.o.} = 90 + 43\ \varphi_m\ (\Delta t_{sub_{OM2}} - 26.3) \qquad (7)$$

or

$$\Phi_{b.o.} = 90 + 43\ \varphi_m\ \Delta t_{sub_{mix}} \qquad (7a)$$

The data scatter is within 4% of the given correlations.

In respect of these correlations it is remarkable, as regards the systems which obey Raoult's law, that based on the saturation temperature of the mixture a correlation is obtained of the same form as for OM2. In contrast, this is not so for the OM2 mixtures with benzene, methane or nitrogen as will be shown below.

Pressure drop

No pressure drops were measured for this system.

d. OM2 with 0.023 wt.% nitrogen

The solubility of nitrogen in OM2 should not differ too much from its solubility in Santowax R (Ref. 4).

This mixture was therefore unsaturated at 2.9 bar and above 240°C.

Burn-out

The influence of nitrogen on the burn-out heat flux of OM2 is slight (about 1 to 6%), although the vapour pressure of the mixture is considerably higher than of pure OM2.

The data were correlated with the following formulae

$$\Phi_{b.o.} = 110 + 27.6\ \varphi_m\ \Delta t_{sub_{OM2}} \qquad (8)$$

or

$$\Phi_{b.o.} = 110 + 27.6\ \varphi_m\ (\Delta t_{sub_{mix}} + 37.8) \qquad (8a)$$

The scatter is within 4% of the correlation.

The vapour tension of this mixture itself is evidently not a characteristic property for the burn-out phenomena.

Pressure drop

No pressure drops were measured for this system.

e. OM2 with 0.025 wt.% methane

Burn-out

The influence of methane on the burn-out heat flux of OM2 does not differ appreciably from that of nitrogen.

The data were correlated with the following formulae

$$\Phi_{b.o.} = 82 + 32.6\ \varphi_m\ \Delta t_{sub_{OM2}} \qquad (9)$$

or

$$\Phi_{b.o.} = 82 + 32.6\ \varphi_m\ (\Delta t_{sub_{mix}} + 54.8) \qquad (9a)$$

The scatter is within 4% of the correlation.

Pressure drop

No pressure drops were measured for this system.

f. OM2 with 15 wt.% high-boilers

The high-boilers were formed radiolytically and were not very stable.

Burn-out

The reproducibility of the burn-out measurements was relatively poor (~8%).

Fig. 8 shows that the critical heat flux (C.H.F.) for 15 wt.% high-boilers in OM2 with subcooling of 35°C is about 10% higher than for pure OM2 for a velocity of about 9 m/sec; about 30% for 7.5 m/sec; about 40% for 5.5 m/sec and 50% for 3.5 m/sec.

The slope of the curves (C.H.F. relative to subcooling) is very steep and within the range of the velocities studied influence of velocity is very slight, especially for low degrees of subcooling.

The vapour pressure of this mixture remained practically unchanged during the burn-out measurements. Though the saturation temperature of the mixture of OM2 with 15% high-boilers is even lower than of a mixture of 0.5 wt.% benzene in OM2 or of pure OM2, the critical heat flux is much greater than of pure OM2.

Pressure drop

No pressure drops were measured for this system.

g. "Orgel cooling liquid" imitation

Burn-out

Although the rather high vapour pressure of this liquid decreased during the burn-out measurement owing to purging between the runs of released gases, the burn-out runs show good reproducibility (<4%).

Fig. 9 indicates the critical heat flux of the "Orgel cooling liquid" compared with pure OM2.

In the region between 180 to 160 W/cm^2 and 40 to 25°C subcooling curves for constant mass velocity intersect. In a subcooling range of 0 to 40°C the C.H.F. of the "Orgel liquid" does not differ appreciably from 0.25 wt.% methane in OM2.

The results again show that the use of the true vapour pressure in determining a degree of subcooling is not sufficient by itself to correlate the critical heat flux for such complex systems.

Pressure drop

No pressure drops were measured.

2. Investigations with pure OM2 in vertical stainless steel ducts of different geometries

a. Grooved tubes

Tube 5 mm inside diameter with helical groove on the interior surface. Depth and width of groove 0.15 mm. Pitches of groove 1 mm and 2 mm respectively. Heated length 500 mm. Hydraulic diameters 5.078 mm and 5.046 mm respectively.

The shape of the grooves is shown in the photographs in Fig. 10.

Burn-out

Fig. 11 gives information on th C.H.F. of degassed OM2 in the 1 mm pitch grooved tube. Fig. 12 represents the measurements of OM2 in the 2 mm pitch grooved tube. For comparison, the curves for the C.H.F. of OM2 in the smooth round tube are also given.

In both cases the C.H.F.'s at high degrees of subcooling have increased remarkably, but there is little difference for small degrees of subcooling.

Inspection of the grooved tubes after the burn-out measurements showed only that the colour of the inner surface had changed from metallic white to carbon black, but no fouling had occurred in the grooves.

Pressure drop

Isothermal friction coefficients for smooth and grooved tubes as occur in

$$\Delta p = f_n \frac{8 L \varphi_m^2}{\pi^2 D^5 \rho}$$

were measured as a function of Reynolds number for OM2 and also for water under steady-state conditions (see Fig. 13).

The smooth tube behaves in accordance with Blasius' formula

$$f_n = 0.3164 \, Re^{-0.25} \qquad (10)$$

Based upon hydraulic diameters the grooved tube with 2 mm pitch shows a coefficient about 16% higher than of the 1 mm pitch tube. This is due not only to the greater groove depth and groove width of the 2 mm pitch tube, but also to the difference in the cross-sectional shape of the groove. This can be clearly seen in the photographs in Fig. 10, which show the 1 mm groove as a single triangle and the 2 mm groove as two superposed triangles.

Although the C.H.F. for either grooved tube at small degrees of subcooling ($< 20^{\circ}C$) does not differ appreciably from that for the smooth tube, the pressure drop at the burn-out point is considerably higher.

b. Finned tube

Circular tube 9.63 mm in diameter deformed to a shape with 9 longitudinal fins along the periphery, form and dimensions resembling those envisaged for Orgel.

A cross-section of the finned tube is shown in Fig. 10. The wet perimeter is 30.35 mm, the cross-sectional area 34.3 mm^2; wall thickness 0.1 mm.

Burn-out

Fig. 14 gives the C.H.F. curves for degassed OM2 in the finned tube compared with the smooth round 5 mm inside diameter tube. For degassed OM2 in the finned tube the decrease

in C.H.F. was found to be considerable.

After injecting 0,5 wt.% benzene into the OM2 load of the loop the decrease in C.H.F. became even more pronounced, as Fig. 15 shows. In this case a comparison is made with the C.H.F. of OM2 with 0,5 wt.% benzene in the smooth round tube.

Pressure drop

Fig. 13 gives information on the average isothermal friction coefficient for the finned tube related to Reynolds number. The data for OM2 and water agree reasonably well with the data for the smooth round tube and the Blasius formula.

c. "Figure eight" shaped tube

The "figure eight" shaped tube, simulating part of the flow section in a fuel-rod cluster.

Its cross-section is shown in Fig. 10. The wet perimeter of the tube is 30.35 mm, the cross-sectional area 34.3 mm^2 and the wall thickness 0.1 mm.

Burn-out

Fig. 16 compares the C.H.F.'s for degassed OM2 in the "figure eight" tube and in the smooth 5 mm diameter tube down to small degrees of subcooling. The reference lines are those of Fig. 7. Fig. 16 shows that for a mass-flow of about 5250 kg/m^2sec the C.H.F.'s do not differ appreciably for the two geometries, but that for a mass flow of 3480 kg/m^2sec the C.H.F. in the figure eight tube decreased by roughly 25% of that in de smooth tube.

After injecting 0.5 wt.% benzene into the OM2 load of the loop the decrease in C.H.F. becomes more pronounced, vide Fig. 17. Comparison is again made with the C.H.F. for 0.5 wt.% benzene in OM2 in the round tube.

Although these latter data were obtained at fairly high degrees of subcooling, it is clear that the C.H.F. in the "figure eight" tube is always lower than in the round tube.

Pressure drop

Fig. 13 gives information on the average isothermal

friction coefficient of the "figure eight" tube related to the Reynolds number. It shows that the friction coefficient for this geometry measured only with water is practically the same as for the smooth round 5 mm inside diameter test tube.

C. Forced convection non-boiling heat transfer and pressure drop of OM2

Heat transfer

Data for forced convection non-boiling heat transfer were correlated with the Sieder and Tate equation

$$Nu = 0.021\ Re^{0.8}\ Pr^{0.4}\ (\eta_b/\eta_{w,w})^{0.14} \qquad (11)$$

The physical properties are taken at the bulk outlet temperature of the test tube. $\eta_{w,w}$ is the viscosity of the fluid at the wet-wall temperature at the outlet.

Owing to the small power supplies in these measurements, the electric power is estimated to be accurate to 6%. The maximum scatter of the data of this correlation is 9%.

The geometry was again the vertical, round stainless steel tube, 4.94 mm inside diameter. The range of variables for these measurements includes an outlet pressure of 2.9 bar, outlet subcoolings from 10 to 70°C and mass-velocities between 0.065 to 0.19 kg/sec. The tube was cleaned with carborundum powder No. 600 giving an "average central line roughness" of 0.8 μ. The roughness was determined with a Talysurf unit, model 3 (make Taylor and Hobson).

The wet-wall temperature for these data was measured through the upper window of the test section, i.e. 4 to 7 mm from the top of the test tube.

Pressure drop

The forced-convection non-isothermal pressure drop measurement across the heated length of the test tube can be calculated by using the following correlation for the non-isothermal friction factor coefficient f_h

$$f_h = f_n - 5.10^{-5} \Phi \tan (111.3\, e^{-25.33\, \varphi_m}) \qquad (12)$$

in which f_h is the friction factor to be used in conjunction with formula (2), with properties evaluated at the average bulk temperature across the test tube; f_n is the friction factor according to formula (10) at a bulk temperature equal to $(t_{sat} - \Delta t_{sub})$.

The friction factor f_h calculation is accurate to about 3%.

The static pressure loss caused by the temperature difference between the fluid in the pressure leads and the fluid in the test tube has been disregarded.

In Fig. 18, the thermal entry effect and the wet-wall temperature distribution along the tube is shown for a mass velocity of 0.065 kg/sec, 70°C subcooling and a static pressure at the outlet of 2.9 bar.

It was not possible to measure the wall temperature for the first 10 cm of the test tube, and the first 10 cm is not therefore included in the figure.

The thermal entry effect is however clearly demonstrated by the curves for $\Phi = 80$ W/cm^2 and $\Phi = 40$ W/cm^2 respectively; at these heat fluxes no boiling occurred.

D. Forced-convection subcooled boiling heat transfer and pressure drop of OM2

Heat transfer

The range of variables for forced-convection subcooled boiling includes an outlet pressure of 2.9 bar for the region of subcooling from 10 to 70°C, mass-velocities of 0.065 to 0.19 kg/sec and heat fluxes up to 335 W/cm^2.

The vertical, round stainless steel 4.94 mm inside diameter test tube was cleaned with carborundum powder No. 600; the "average central line roughness" was 0.8 μ (Talysurf model 3).

The vapour pressure of the OM2 loads deviated from the given curve by not more than 3%.

The subcooled boiling data were correlated by the method of least squares for linear regression on the logarithms.

The following equation was obtained

$$Nu = 9.1 \left(\frac{(t_{w,w} - t_{b,out})\, c_{p_{b,out}}}{r_{sat}} \right)^{3.5} \left(Re_{b,out} \right)^{0.3} \times$$

$$\times \left(\frac{r_{sat}}{c_{p_{b,out}} (\Delta t_{sub_{OM2}} + 37)} \right)^{2.7} \qquad (13)$$

standard deviation s = 0.06
correlation coefficient R = 0.99

The 110 measurements are described by the formula including about 20 subcooled burn-out runs, with an accuracy of about ± 5%.

The Nusselt number is based on local values of heat transfer coefficients at the outlet of the test tube.

The equation can only be applied to subcooled boiling. Further studies are required to determine the suitability of the correlation for saturated boiling data, i.e. when $\Delta t_{sub_{OM2}} = 0$.

Pressure drop

The pressure drop across the heated test tube (500 mm length and 4.94 mm inside diameter) can be predicted by the following correlation of the non-isothermal friction factor f_h

$$f_h = 0.0105 + 10^{-4} (\Phi + 24) \tan (99.26\, e^{-11.16\, \varphi_m} - 5.255\, 10^{-3}\, \Delta t_{sub}) \qquad (14)$$

This equation is used in conjunction with the equation (2) with properties evaluated at the average bulk temperature over the test tube.

The equation correlating the friction factor is accurate to 4%, the burn-out pressure drops included.

Further study is to be made to investigate the applicability of the formulae for different pressures, diameters and lengths of the test tube and different fluids.

E. Working diagram for pure OM2

All the final results for heat transfer and pressure loss are fully incorporated in the working diagram given separately in the back cover of this report. On the basis of the correlations mentioned, the diagram has been calculated for mass-velocities of 0.20, 0.15, 0.10 and 0.05 kg/sec and subcoolings of 10°, 30°, 50° and 70°C.

The burn-out curves are extended to low degrees of subcooling using the experimental results.

The diagram is self-explanatory and can be used without reference to this report. The results obtained with this diagram will not on the whole deviate from values obtained experimentally by more than 5%.

F. Miscellaneous

In general, the onset of nucleate boiling (O.N.B.) for a given coolant is a function of coolant velocity and superheating of the wall, which in turn depends on the vapour pressure of the coolant.

Because of uncertainties regarding the actual coolant composition (small unknown amounts of dissolved gas, water or low-boilers) during measurement of one and the same load, no specific measurements of the O.N.B. heat fluxes were made. Moreover, fouling deposits of unknown resistance may impede the rate of superheating of the wall.

The terphenyl mixture used in the experiments was technical grade OM2 made by Progil (France). Analyses of samples of OM2 gave only the o-, m- and p-terphenyl content and an estimate of the quantities of diphenyl and heavy products.

With gas chromatography or thin-layer chromatography, the high-boilers are in both cases quantitatively determined as the difference between the weight of a sample and the measured quantities of o-, m- and p-terphenyls. None of these methods can determine benzene, small quantities of diphenyl and other low-boilers. Hence the analyses are not reliable as regards the quantities of low and high-boilers.

The analysis given by the manufacturer was the same for every

lot of OM2, i.e.

diphenyls <1%
o-terphenyl 25%
m-terphenyl 70%
p-terphenyl <5%
"point apparition des premiers cristaux" $\leq 90^{\circ}C$
"palier de cristallisation" $\leq 76^{\circ}C$
"la teneur en eau" <50 ppm

In general it may be said that the liquid content of the loop was renewed frequently enough to keep the isomeric composition of the liquid within narrow limits.

The best control over the change in composition of OM2 or its mixtures was repeated checks on the vapour pressure of the fluid, which was not allowed to change by more than 3% of the virgin composition vapour pressure. The composition of mixtures of OM2 with low-boilers and gases is accurate to about 0.002 wt.%.

Visual examination of the internal surfaces of several damaged test tubes revealed traces of deposit of decomposition products. A carbon black-like crust is produced on the burn-out spot of the test pipe.

It was observed that after replacing a test tube with a new one, the liquid remaining unaltered, the first two or three burn-out tests differ. It is not certain, however, whether this is due only to the altered surface of the test tube since, during the time of replacement, the low-boiler content of the liquid may change. It is also possible that during the first burn-out tests after a period of non-activity there is fairly strong divergence from thermodynamic equilibrium between liquid and gas. This might explain why similar deviations from the first burn-out results were occasionally found without a new test tube being fitted. In general it can be said that even in the case of the test tube which suffered from about 400 burn-outs, there was no detectable effect on burn-out results from changing surface conditions of the test tube. The results of the subcooled boiling data were reproducible to within 3% for two test tubes which were cleaned and altered in the same way.

ACKNOWLEDGMENTS

The valuable assistance of Mr. L.M. Rappoldt and Mr. S.T. Lim is gratefully acknowledged.

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(4) R.W. Bowring, et al. — "The physical properties of Santowax R for heat transfer calculations" AEE Report W-M 118, March 1961

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SYMBOLS

$t_{w,d}$ (°C) = outside wall temperature of test tube measured with radiation pyrometer

$t_{w,w}$ (°C) = inside wall temperature of test tube

t_{sat} (°C) = saturation temperature at operating pressure of 2.9 bar

$t_{b,in}$ = bulk temperature at the inlet

$t_{b,out}$ = bulk temperature at the outlet

$\bar{t}_b$ (°C) = $\frac{1}{2}$ ($t_{b,in}$ + $t_{b,out}$), average bulk temperature of fluid in test tube

$\Delta t_{sub_{OM2}}$ (°C) = degree of subcooling at outlet based on saturation temperature of pure OM2

$\Delta t_{sub_{mix}}$ (°C) = degree of subcooling at outlet based on saturation temperature of mixture in study

Δt_{sat} (°C) = $t_{w,w} - t_{sat}$

Φ(W/cm^2) = average heat flux density for upper 10 cm of test tube

$\Phi_{b.o.}$(W/cm^2) = average burn-out heat flux density for upper part of test tube

φ_m (kg/sec) = mass-velocity in test tube of 5 mm inside diameter

$c_{p_{b,out}}$ (kJ/kg°C) = specific heat of fluid at bulk temperature at the outlet

$r_{t_{sat}}$ (kJ/kg) = heat of vaporisation for OM2 at saturation temperature

Δp (bar) = pressure drop across heated section (500mm length) of test tube

f_h = friction factor for heated section of test tube under non-isothermal flow conditions, in

$$\Delta p = \frac{8}{\pi^2} \cdot f_h \cdot \frac{L\varphi_m^2}{\rho D^5}$$

f_n = friction factor for heated section of test tube under isothermal flow conditions, in

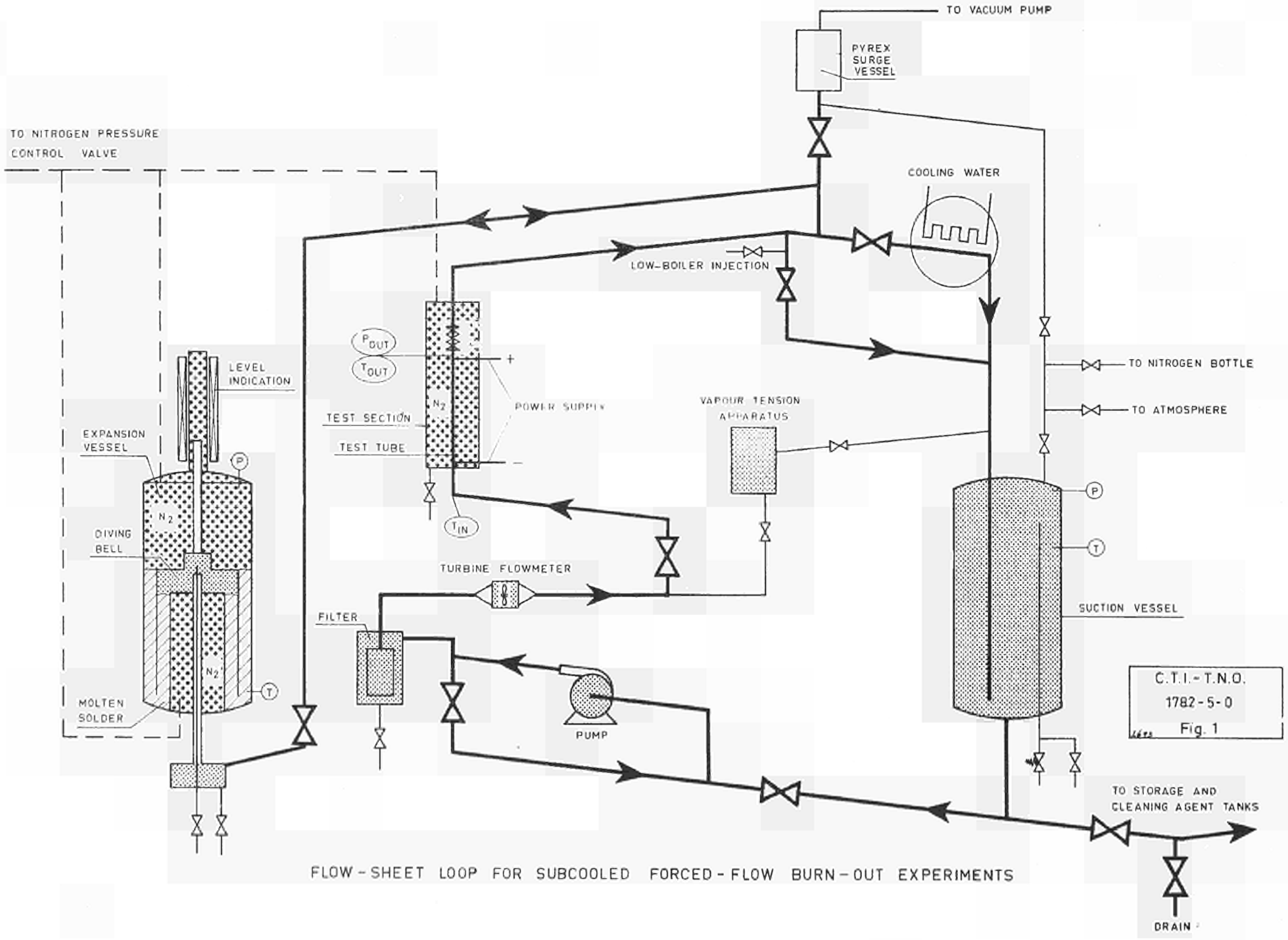
$$\Delta p = \frac{8}{\pi^2} \cdot f_n \cdot \frac{L\varphi_m^2}{\rho D^5}$$

d (m) = wall thickness of test tube

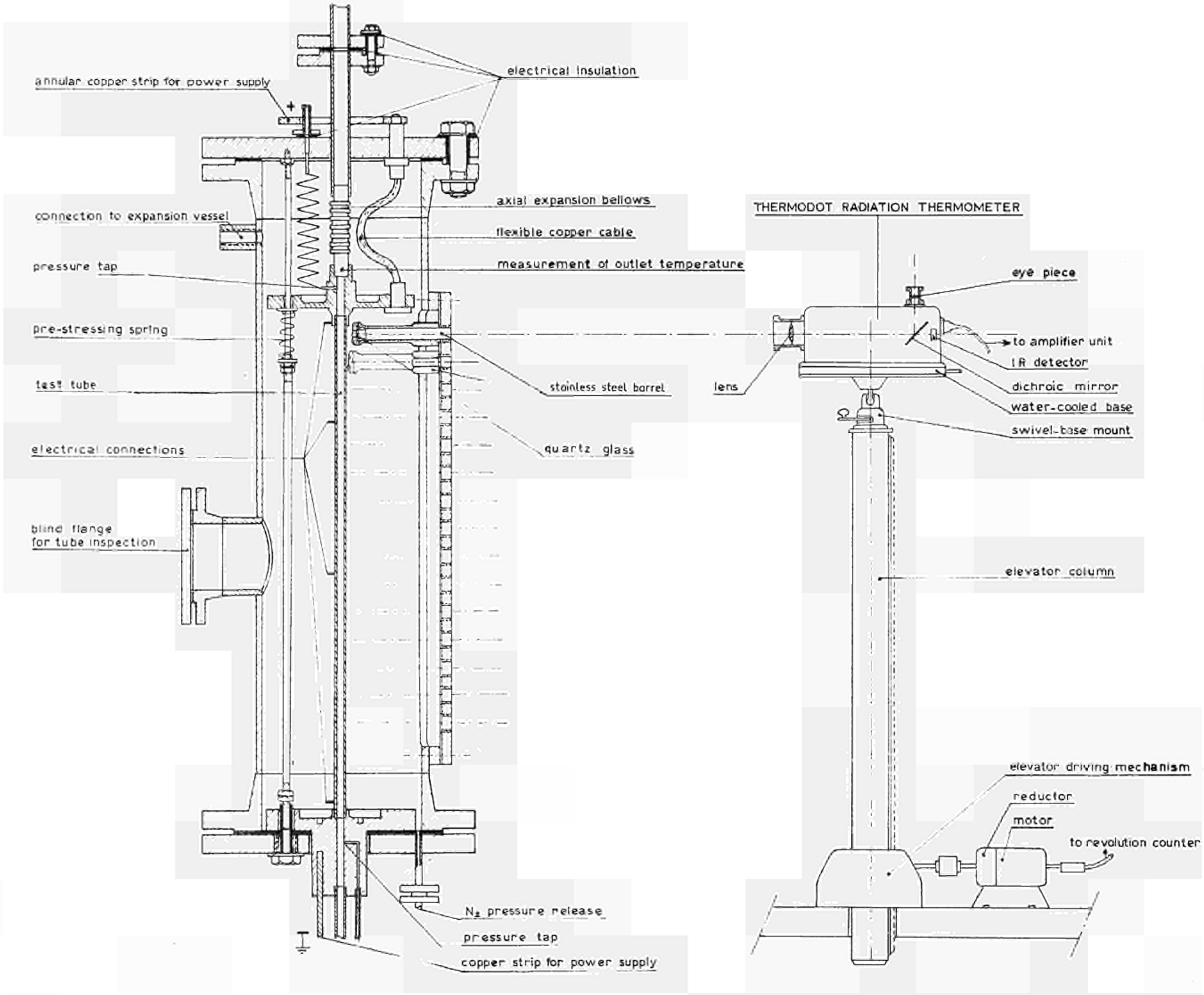
D (m) = inner diameter of test tube

L (m) = length of heated section of test tube (500 mm)

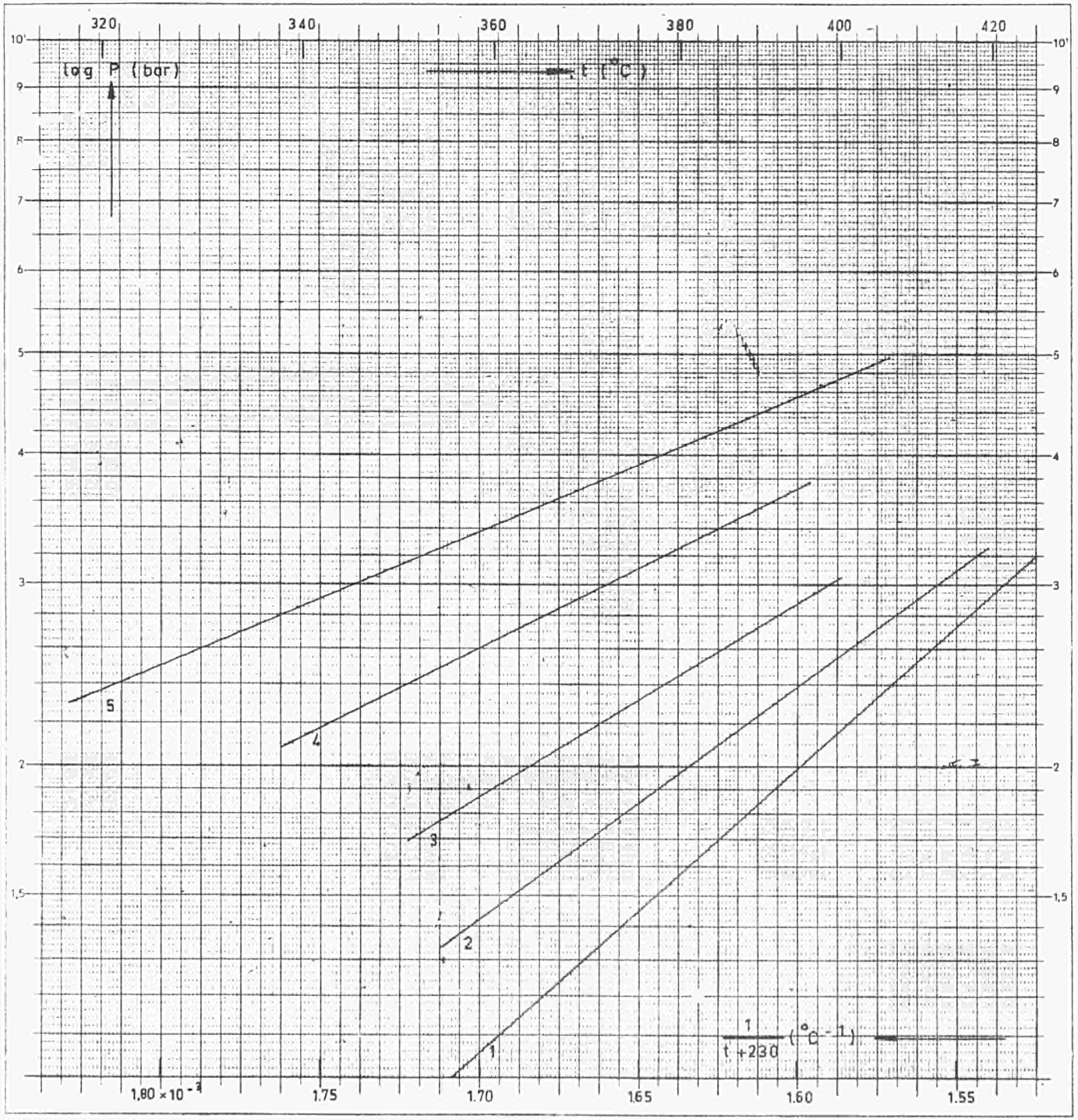
ρ (kg/m^3) = density of fluid



FLOW-SHEET LOOP FOR SUBCOOLED FORCED-FLOW BURN-OUT EXPERIMENTS



Test section and radiometer set - up	C.T.I. - T.N.O. 1782 - 5 - 0 Fig. 2



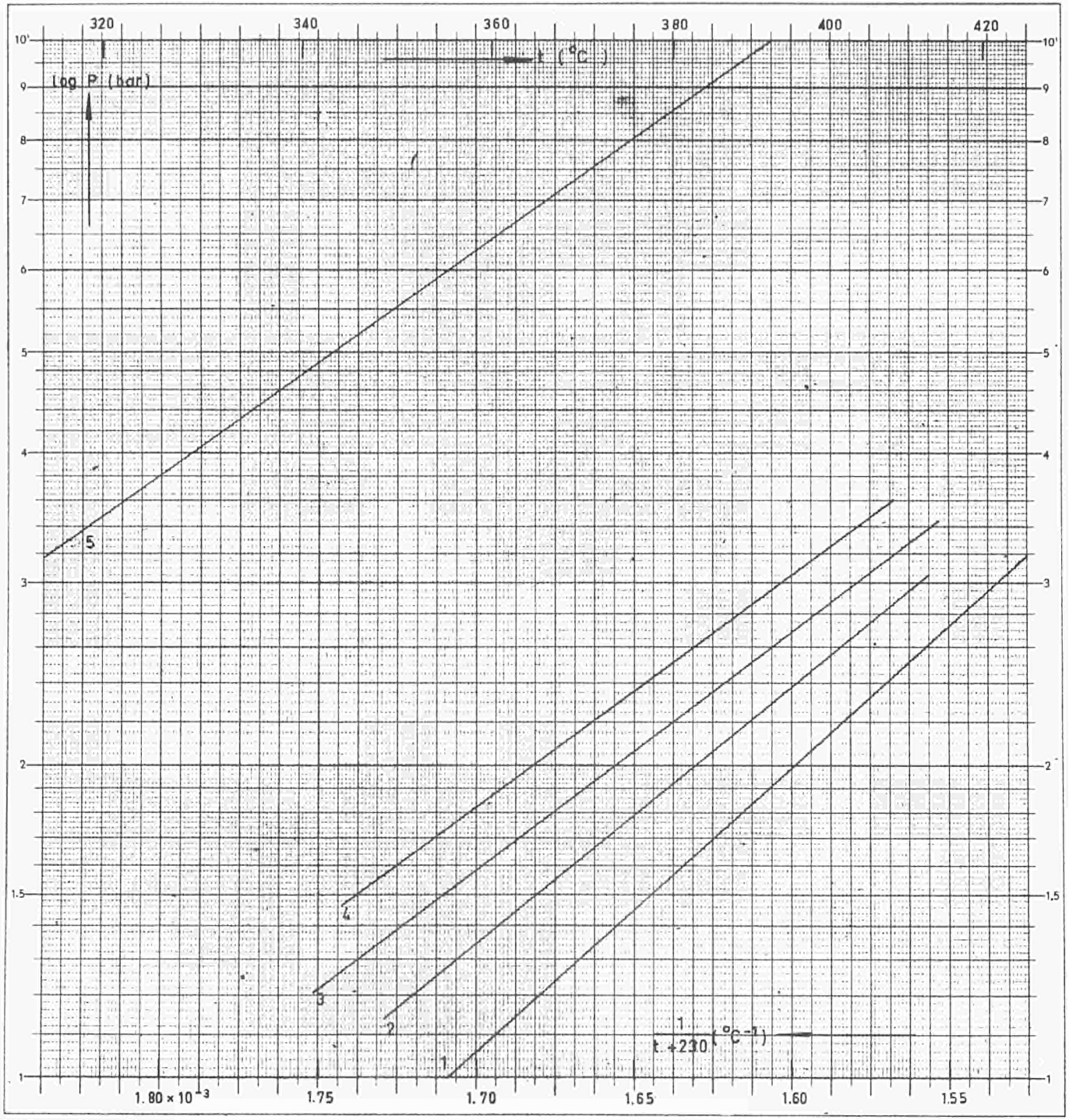
Vapour-pressure curves of OM_2 and OM_2 mixtures

1. OM_2 pure
2. OM_2 + 0.2 wt.% benzene
3. OM_2 + 0.5 wt.% benzene
4. OM_2 + 1 wt.% benzene
5. OM_2 1.5 wt.% benzene

C.T.I. – T.N.O.
1782-5-0
Fig. 3

N.V. Drukkerij „Mercurius" Wormerveer No. 9

X-as verdeeld in mm Y-as log verdeeld 1-10' Eenheid 250 mm



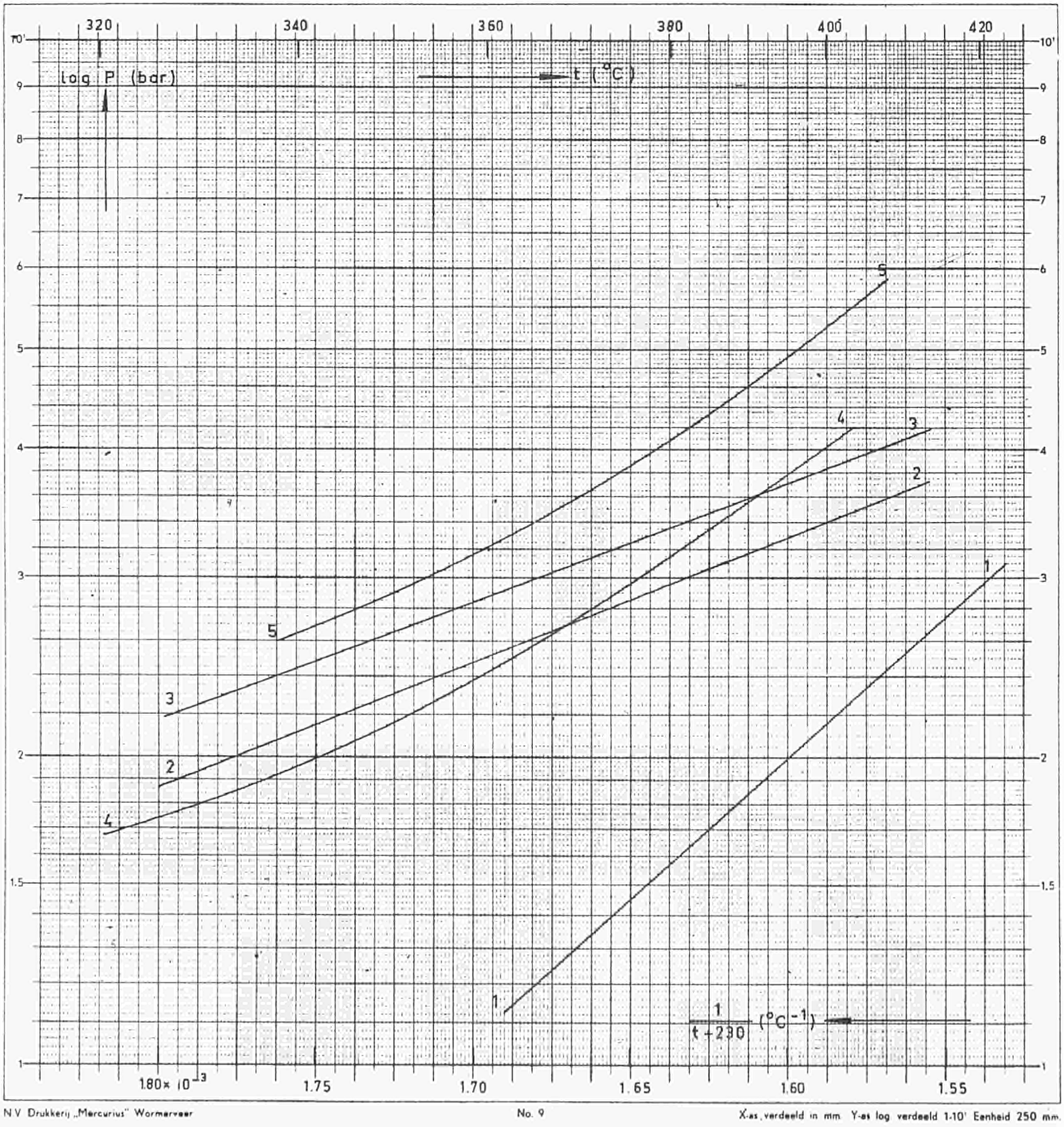
Vapour-pressure curves of OM_2 and OM_2 mixtures

1. OM_2 pure
2. OM_2 + 3 wt.% diphenyl
3. OM_2 + 6 wt.% diphenyl
4. OM_2 + 9 wt.% diphenyl
5. diphenyl Monsanto Chem. Cy. 1958

C.T.I. – T.N.O.
1782 - 5 - 0
Fig. 4

N.V. Drukkerij „Mercurius" Wormerveer No 9

X-as verdeeld in mm. Y-as log. verdeeld 1-10' Eenheid 250 mm.



Vapour-pressure curves of OM_2 and OM_2 mixtures

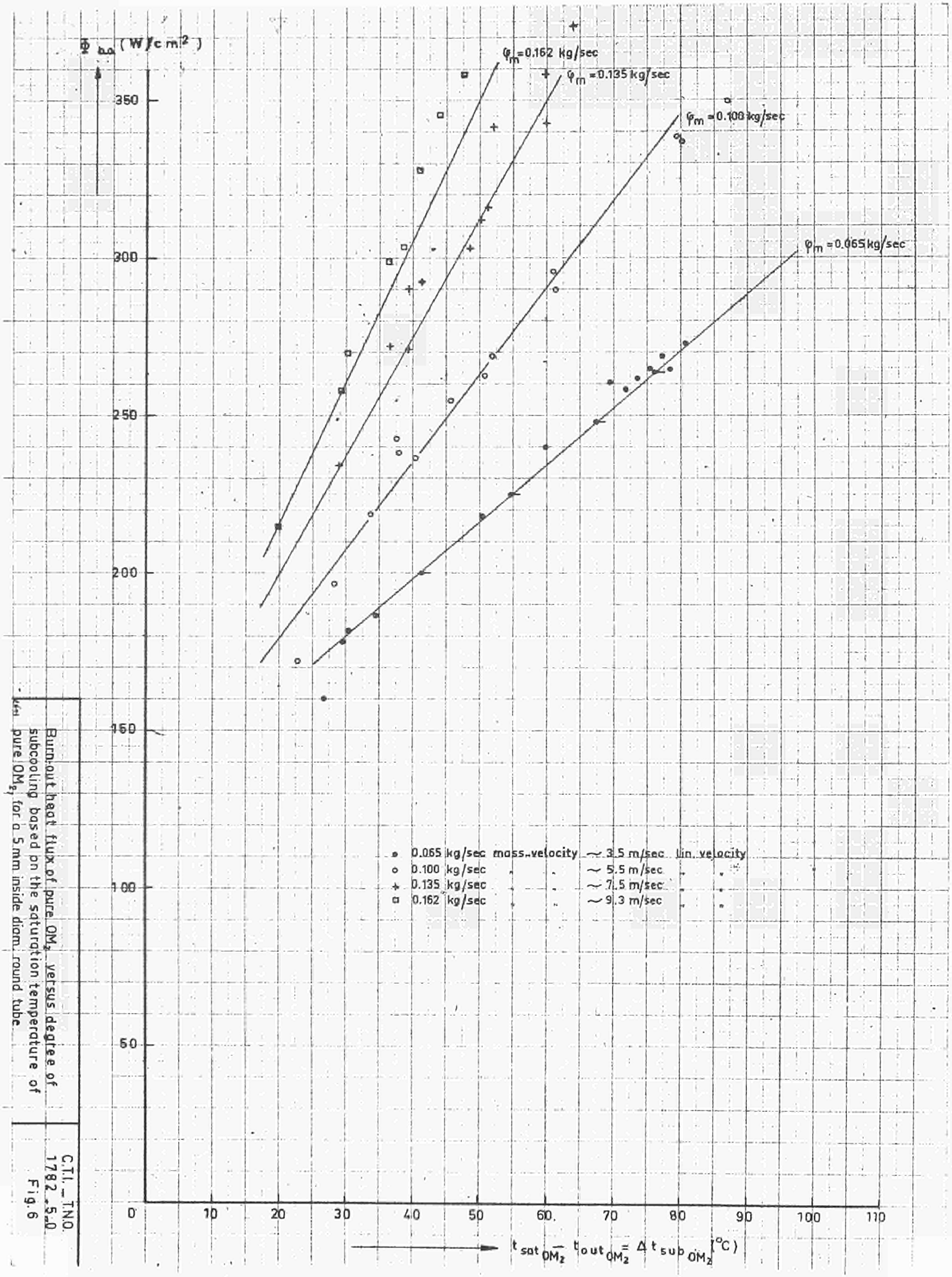
1 OM_2 pure
2. OM_2 + 0.023 wt.% nitrogen
3. OM_2 + 0.025 wt.% methane
4. OM_2 + 15 wt.% high-boilers
5. "Orgel cooling liquid" imitation

C.T.I. – T.N.O.
1782 - 5 - 0
Fig. 5

N.V. Drukkerij „Mercurius" Wormerveer

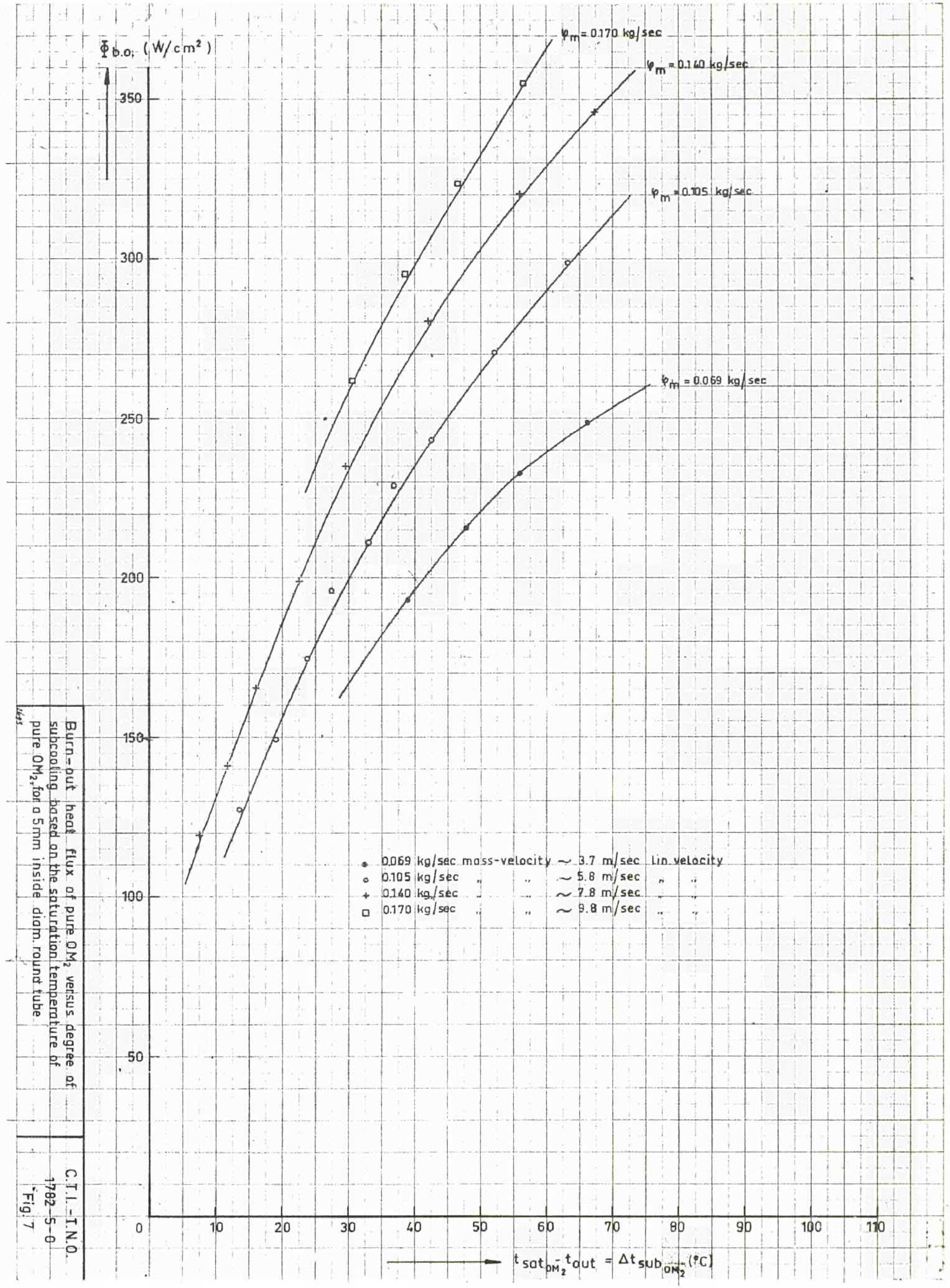
No. 9

X-as, verdeeld in mm. Y-as log. verdeeld 1-10' Eenheid 250 mm.



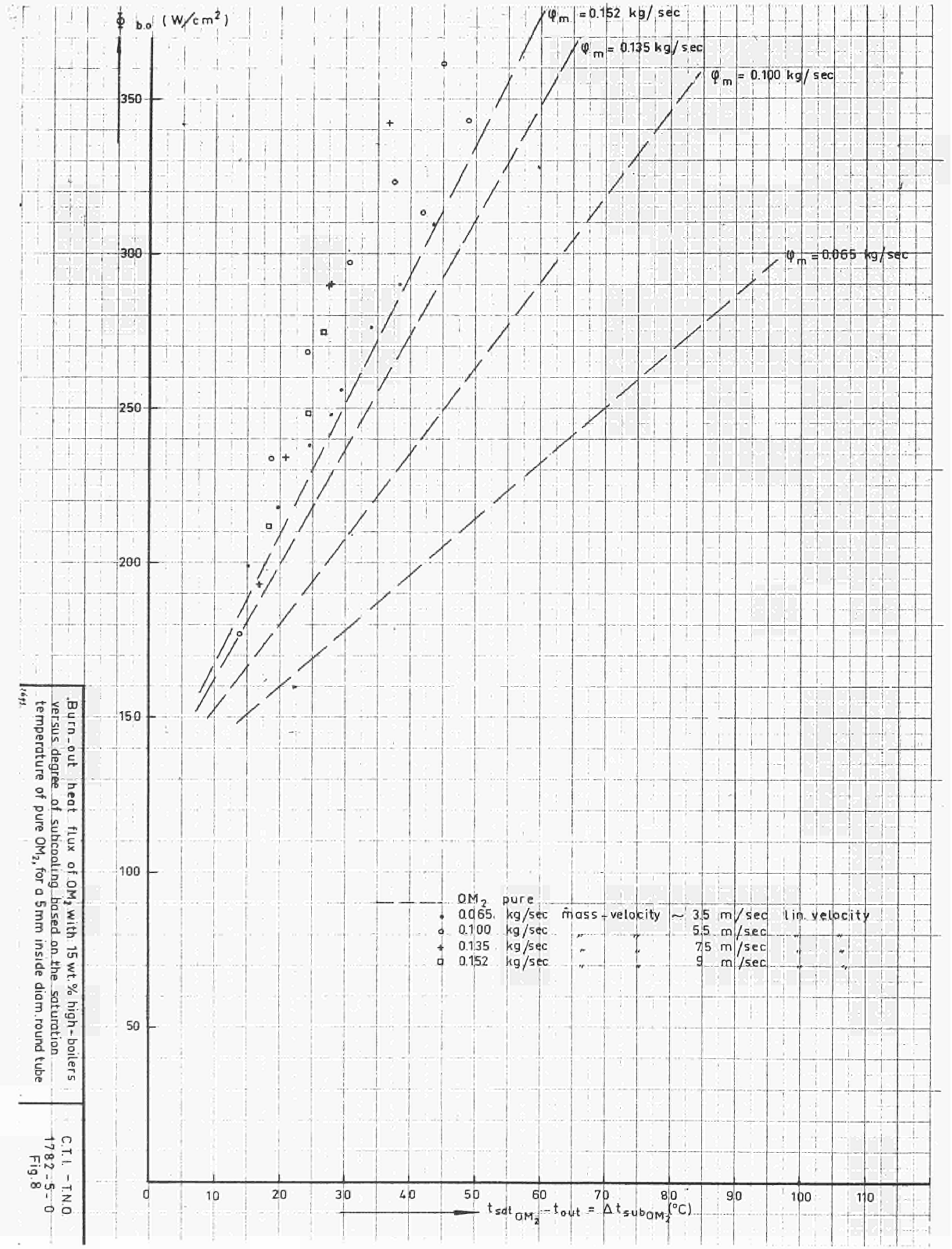
Burn-out heat flux of pure OM_2 versus degree of subcooling based on the saturation temperature of pure OM_2 for a 5 mm inside diam. round tube

C.T.I. – T.N.O.
1782 - 5.0
Fig. 6



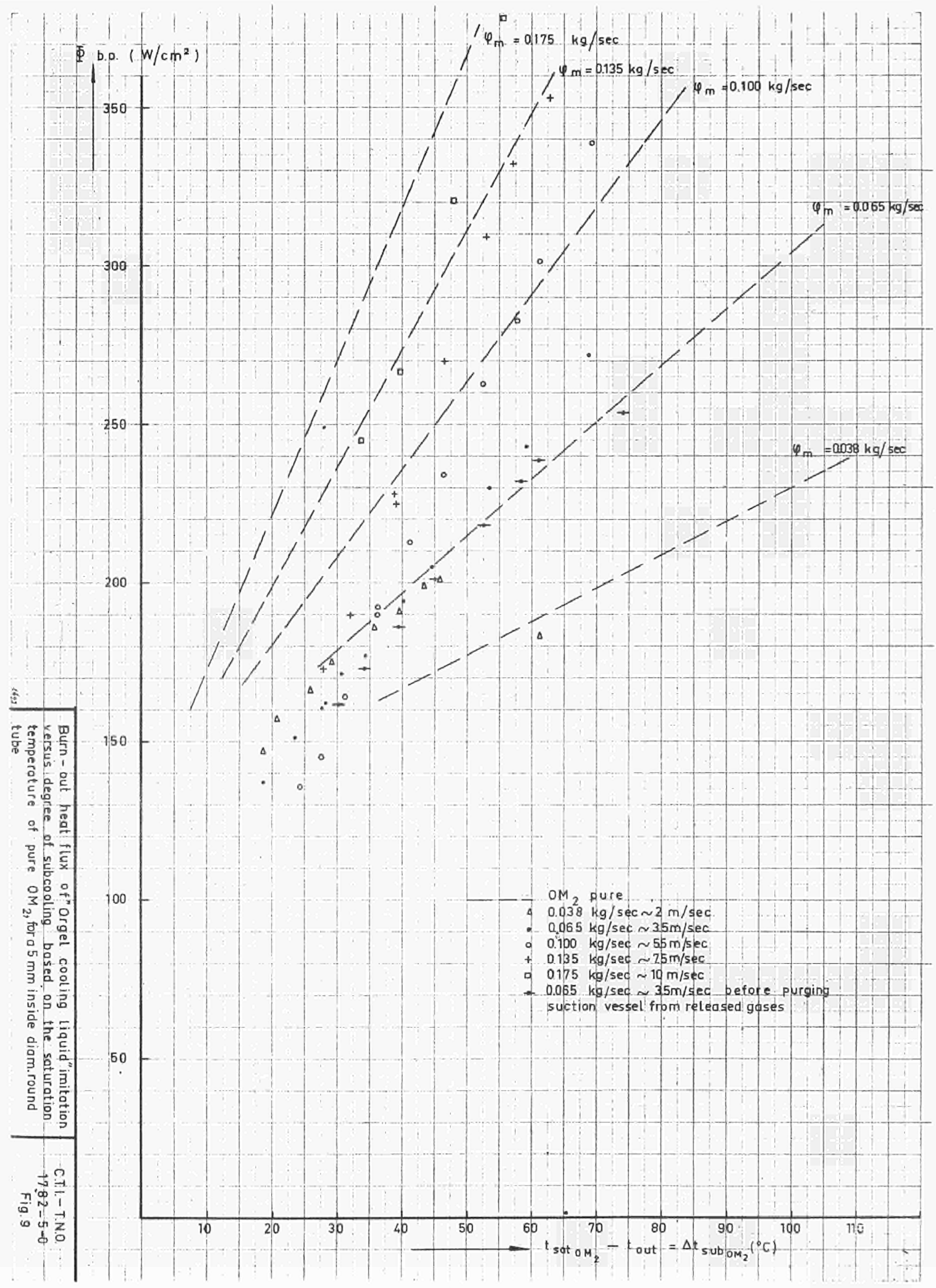
Burn-out heat flux of pure OM_2 versus degree of subcooling based on the saturation temperature of pure OM_2, for a 5mm inside diam. round tube

C.T.I.-T.N.O.
1782-5-0
Fig. 7



Burn-out heat flux of OM_2 with 15 wt.% high-boilers versus degree of subcooling based on the saturation temperature of pure OM_2, for a 5 mm inside diam. round tube

C.T.I. - T.N.O.
1782-5-0
Fig. 8



Burn-out heat flux of "Orgel cooling liquid" imitation versus degree of subcooling based on the saturation temperature of pure OM_2, for a 5 mm inside diam. round tube

C.T.I. – T.N.O.
17.82-5-0
Fig. 9

lengthwise section of 1 mm pitch helically grooved tube

lengthwise section of 2 mm pitch helically grooved tube

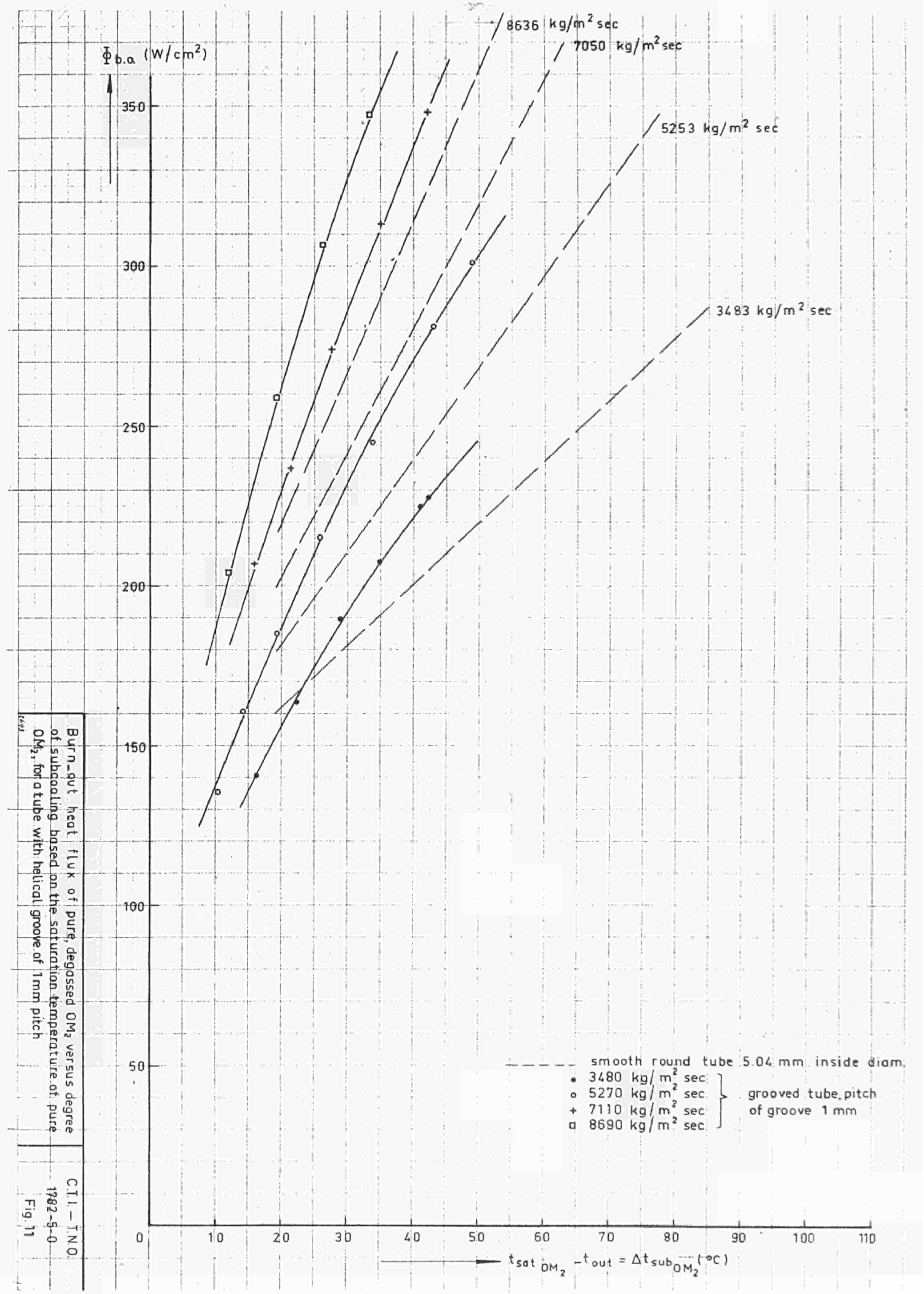
cross-section of finned tube

cross-section of figure eight shaped tube

Sectional photographs of tubes of different geometries

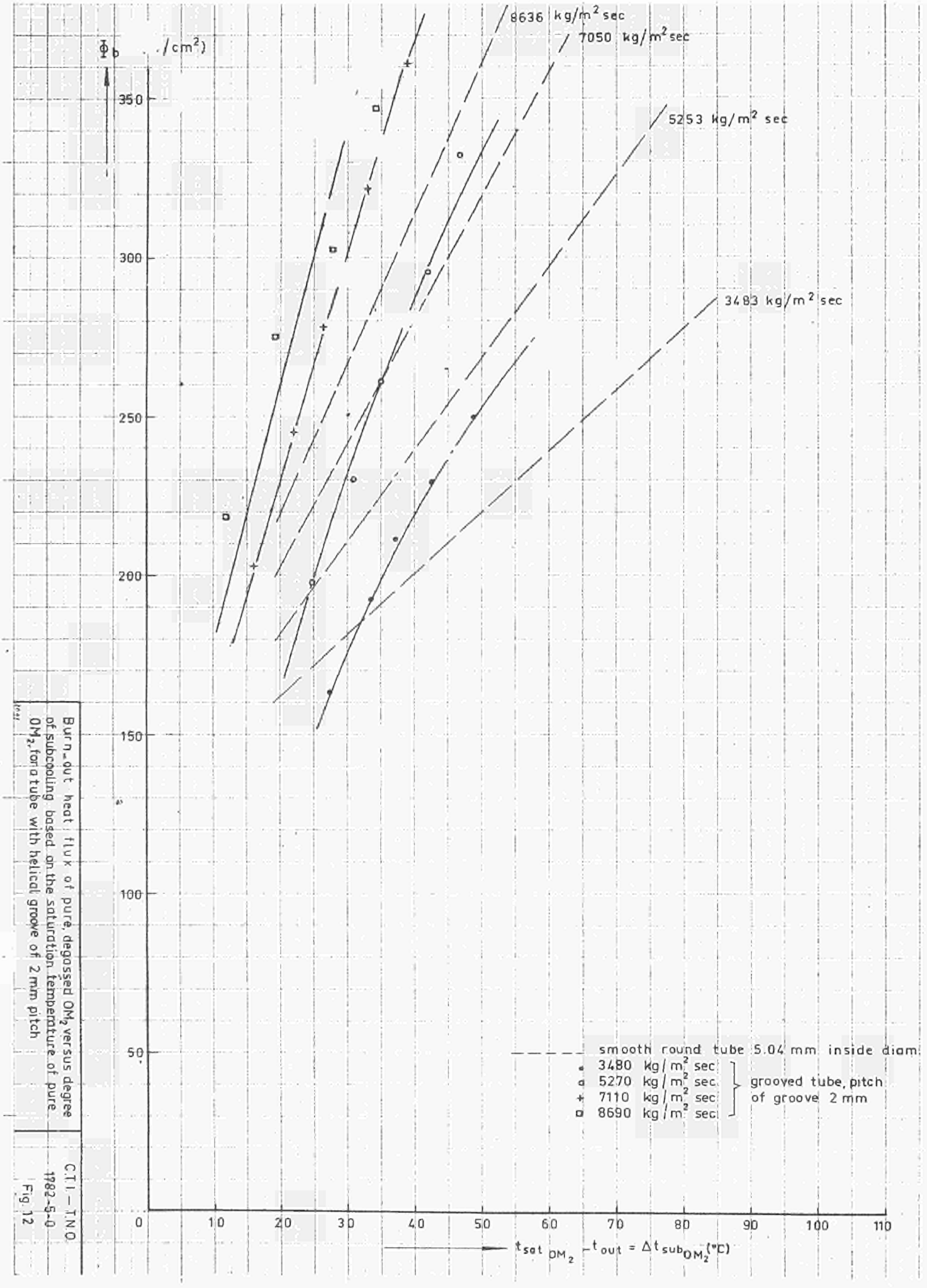
C.T.I. – T.N.O.
1782 - 5 - 0
Fig. 10

4693



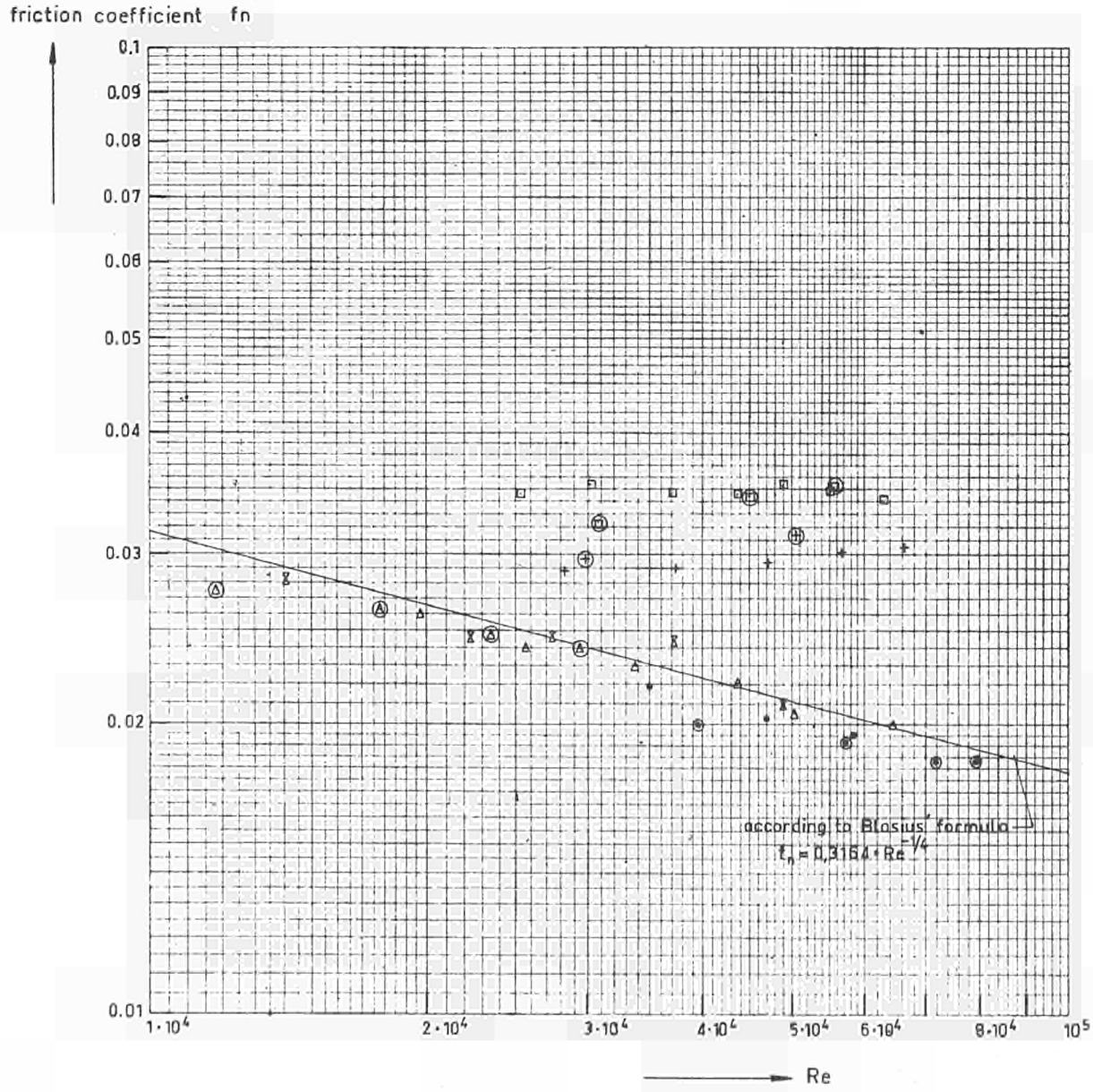
Burn-out heat flux of pure, degassed OM_2 versus degree of subcooling based on the saturation temperature of pure OM_2, for a tube with helical groove of 1 mm pitch

C.T.I. – T.N.O.
1982-5-0
Fig. 11



Burn-out heat flux of pure, degassed OM_2 versus degree of subcooling based on the saturation temperature of pure OM_2, for a tube with helical groove of 2 mm pitch

C.T.I. – T.N.O.
1982-5-0
Fig. 12



Isothermal
friction coefficient
vs. Reynolds number

smooth round tube
» water
◉ degassed OM_2

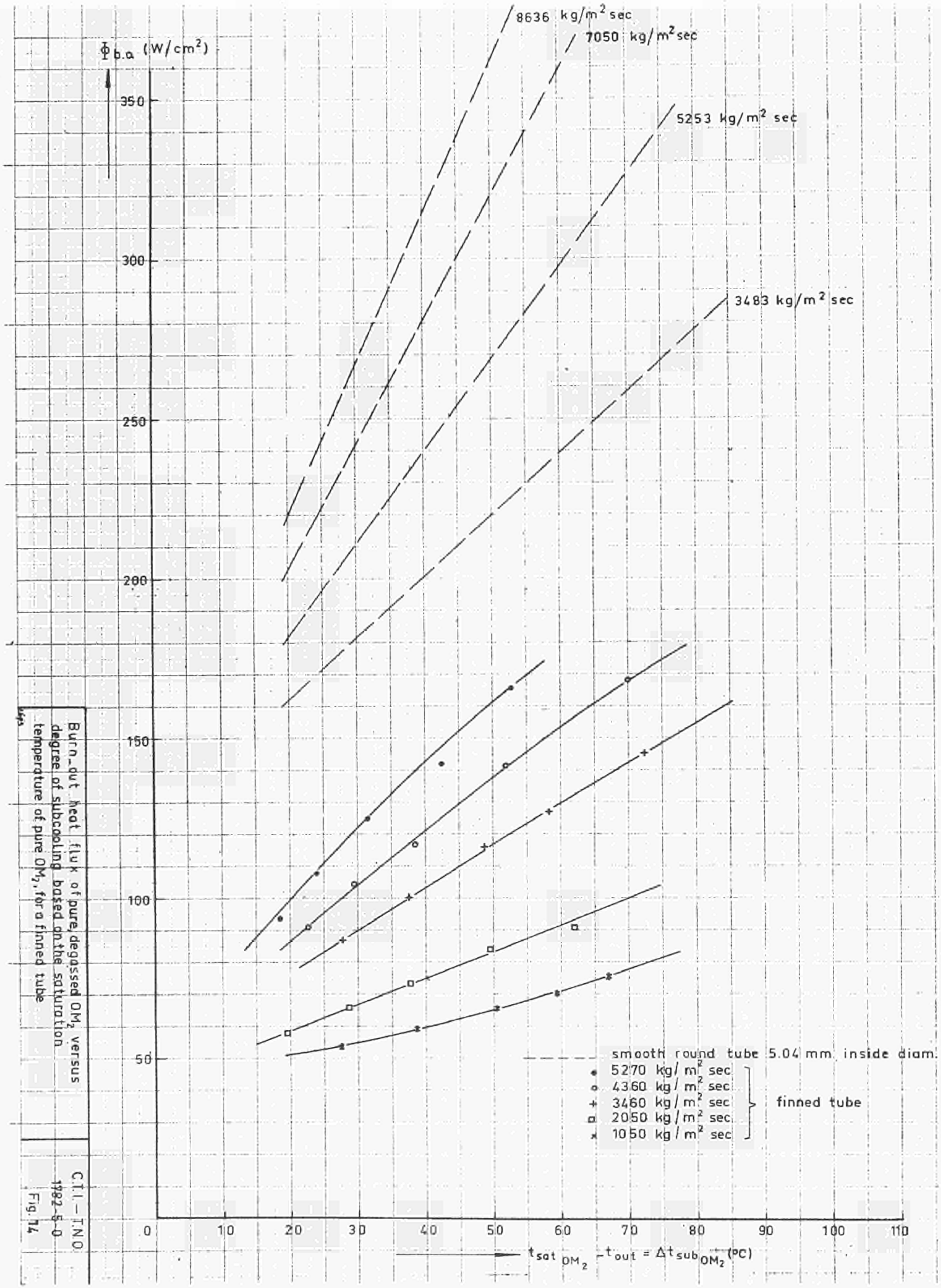
grooved tube, 1mm pitch
+ water
⊕ degassed OM_2

grooved tube, 2mm pitch
▫ water
⊡ degassed OM_2

finned tube
△ water
Ⓐ degassed OM_2

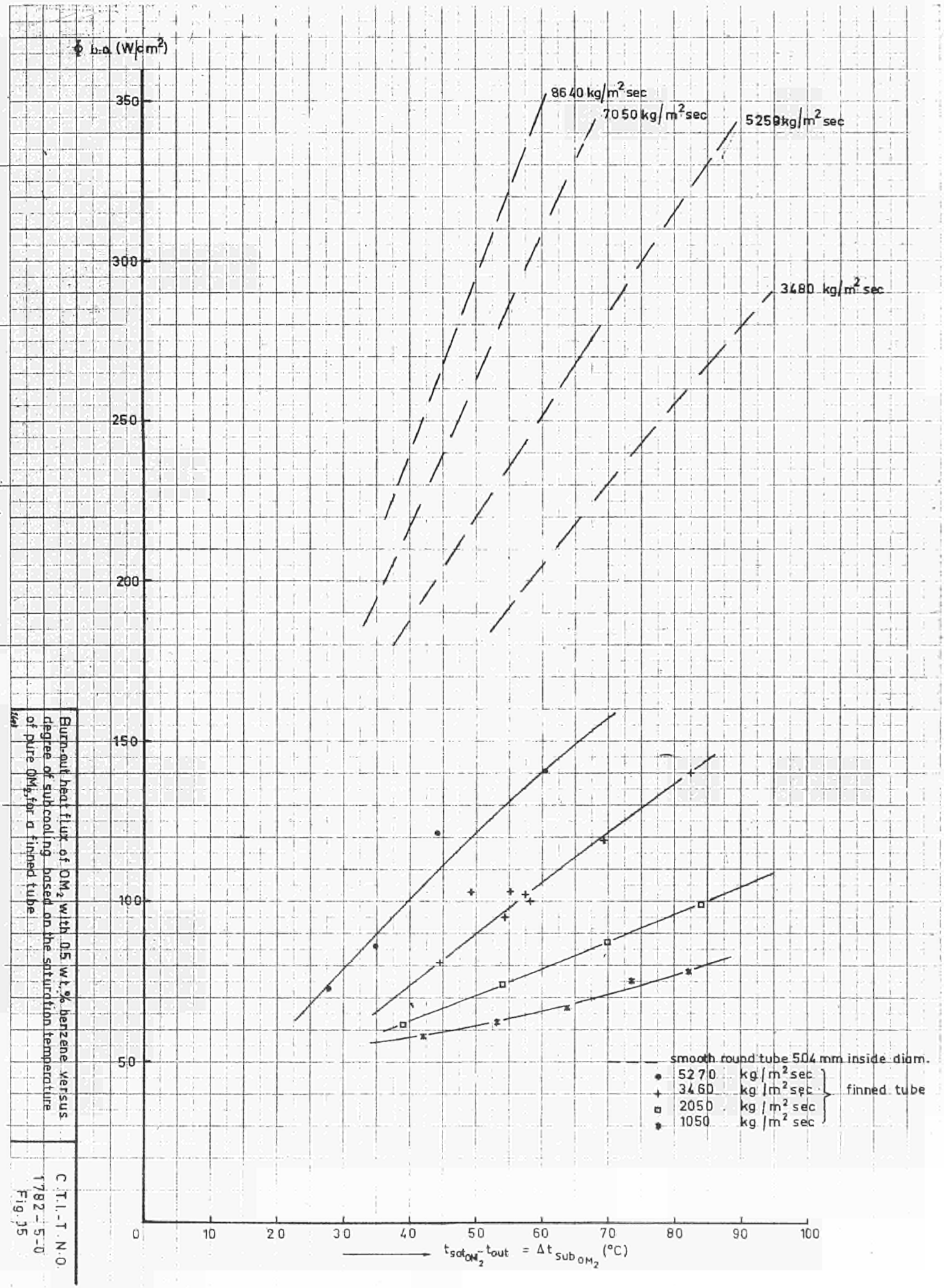
"figure eight" shaped tube
⧖ water

C.T.I. - T.N.O.
1782 - 5 - 0
Fig. 13



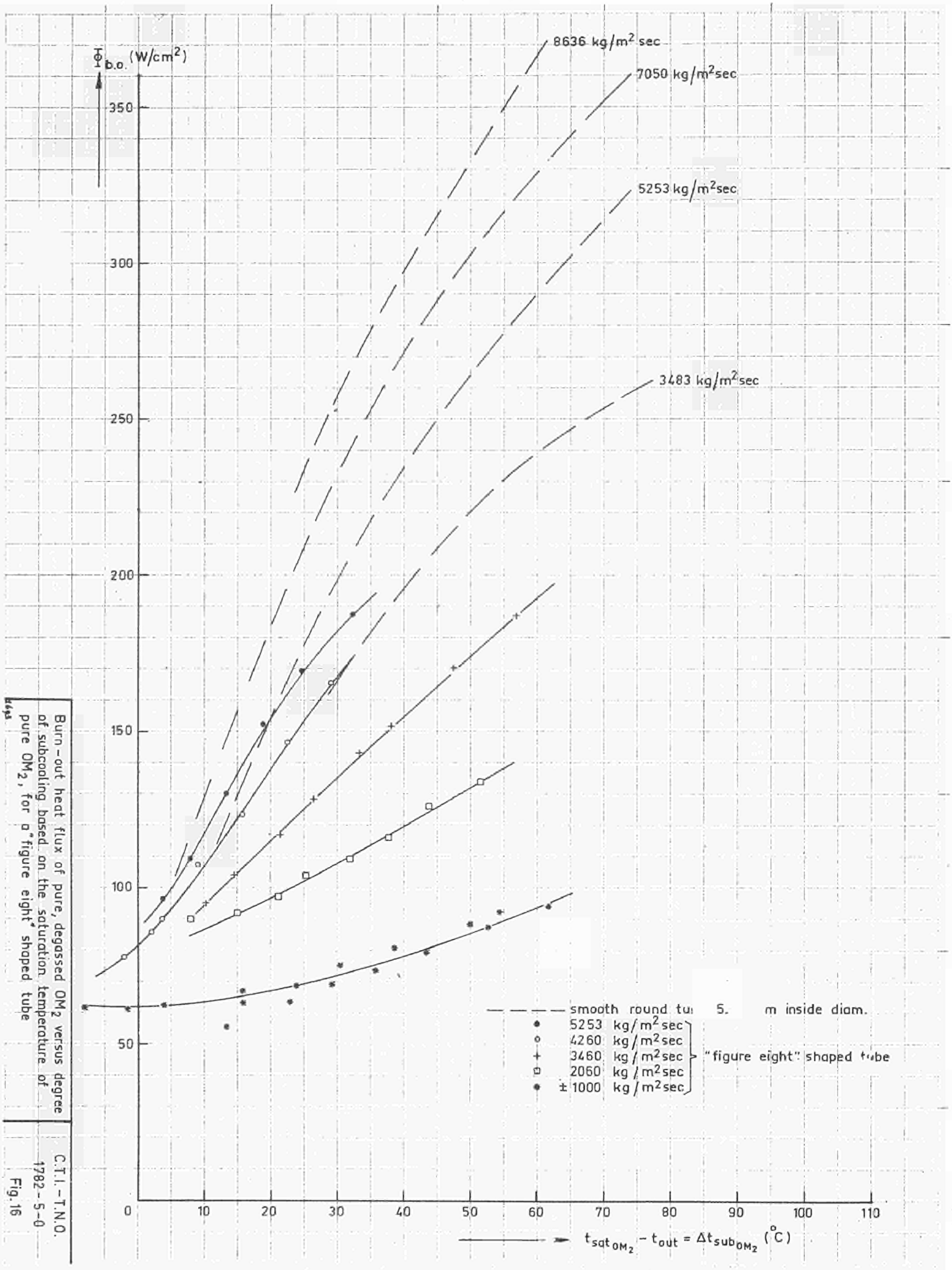
Burn-out heat flux of pure, degassed OM_2 versus degree of subcooling based on the saturation temperature of pure OM_2, for a finned tube

C.I.I. – T.N.O.
1982-5-0
Fig. 14



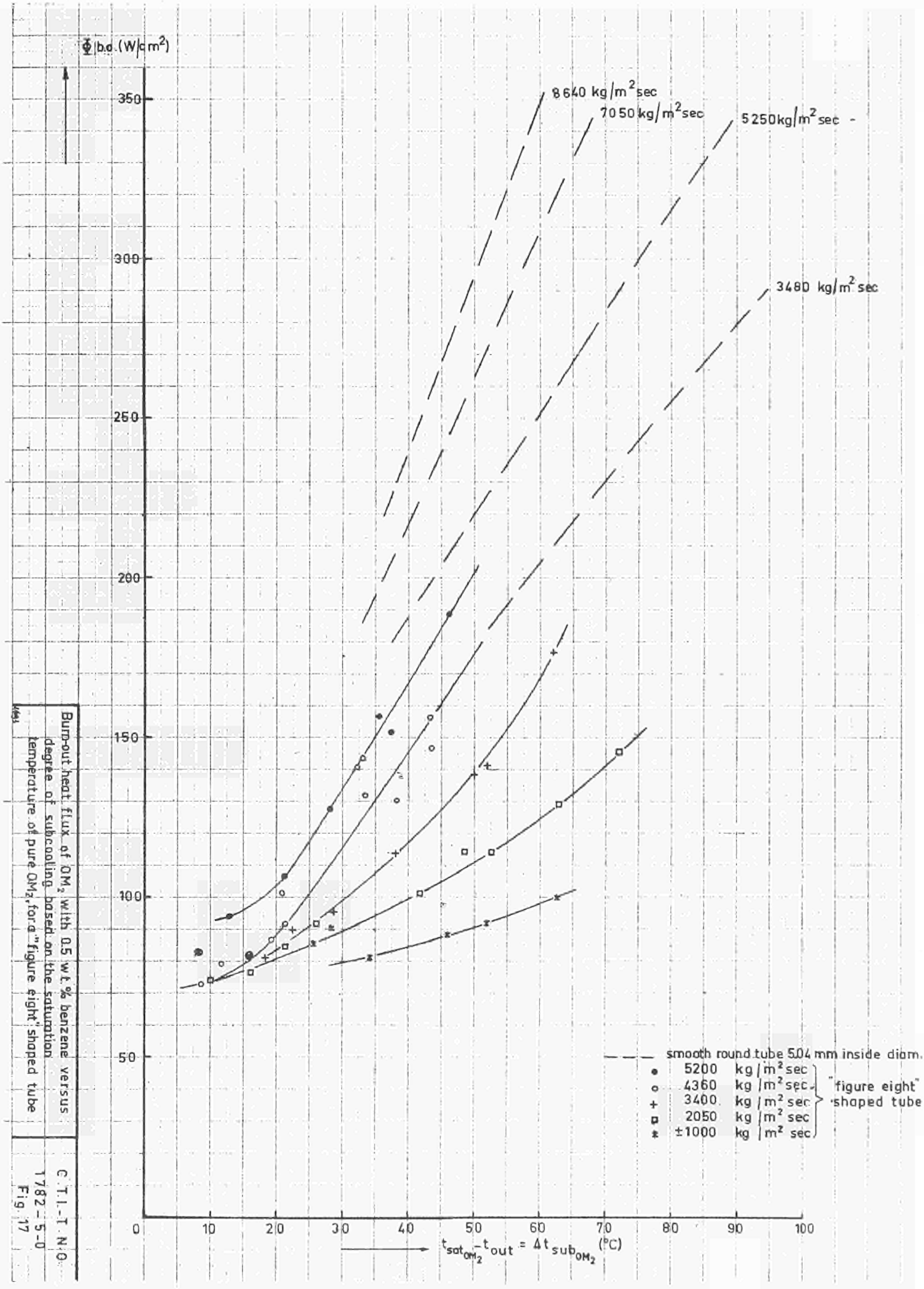
Burn-out heat flux of OM_2 with 0.5 wt.% benzene versus degree of subcooling based on the saturation temperature of pure OM_2 for a finned tube

C.T.I.-T.N.O.
1782-5-0
Fig. 35



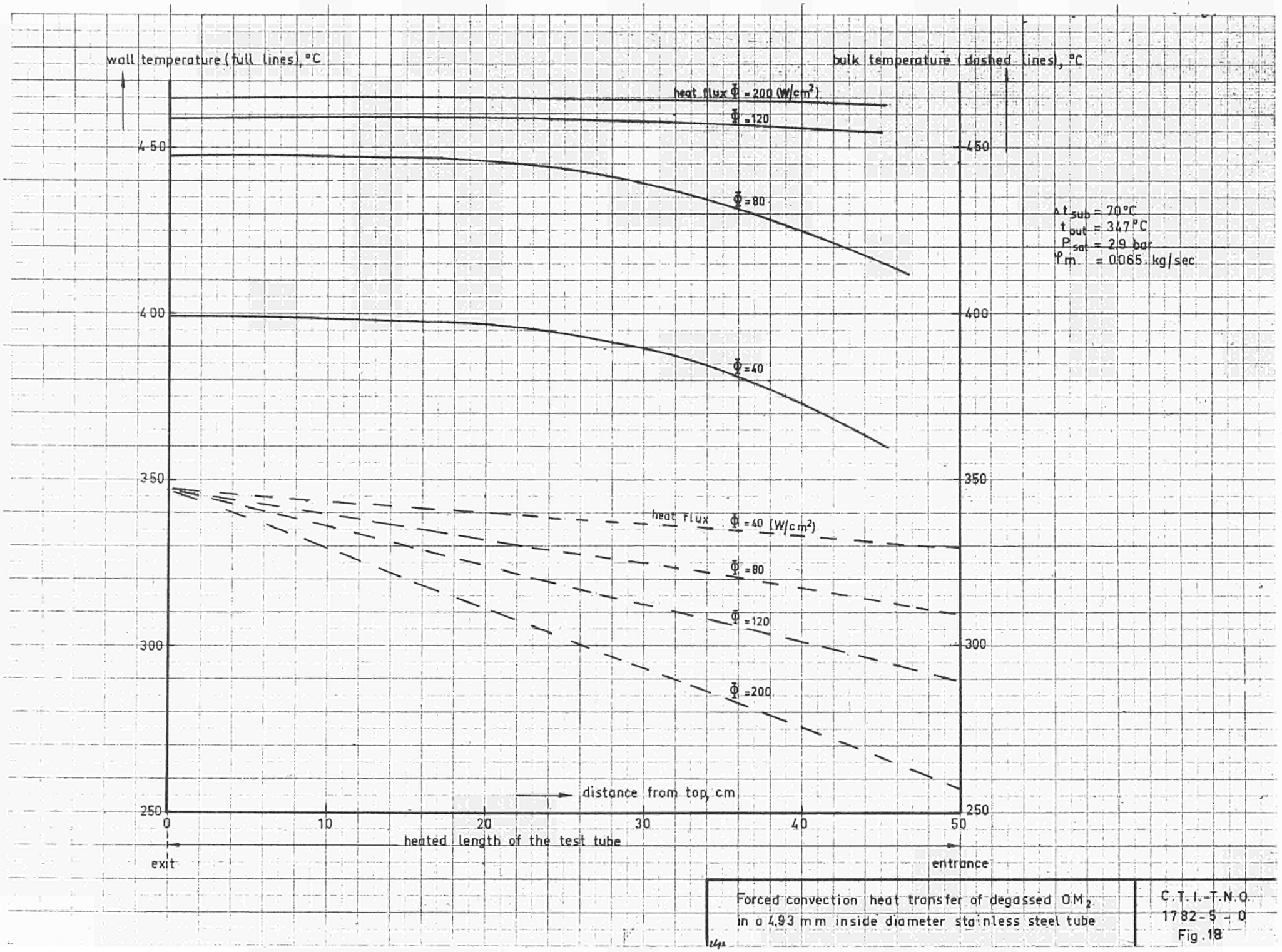
Burn-out heat flux of pure, degassed OM_2 versus degree of subcooling based on the saturation temperature of pure OM_2, for a "figure eight" shaped tube

C.T.I.-T.N.O.
1782-5-0
Fig. 16



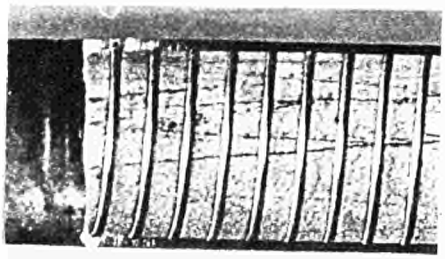
Burn-out heat flux of OM_2 with 0.5 wt.% benzene versus degree of subcooling based on the saturation temperature of pure OM_2 for a "figure eight" shaped tube

C.T.I.-T.N.O.
1782-5-0
Fig. 17

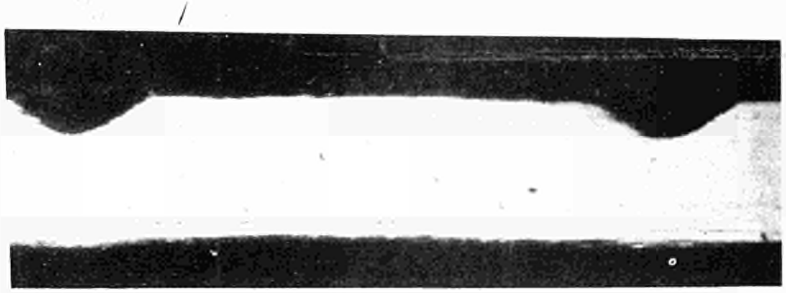


Forced convection heat transfer of degassed CO_2 in a 4.93 mm inside diameter stainless steel tube

C.T.I.-T.N.O.
1782-5-0
Fig. 18

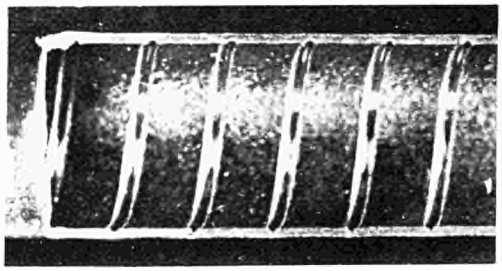


10 mm

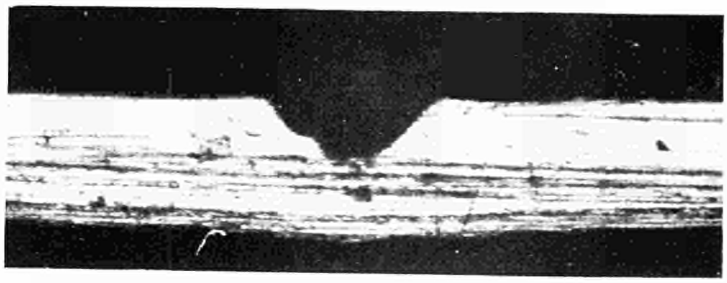


1 mm

lengthwise section of 1 mm pitch helically grooved tube

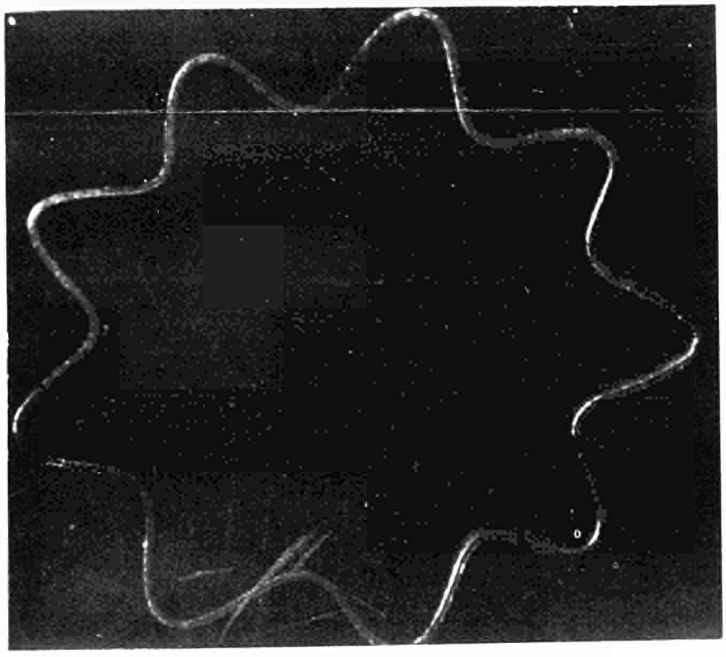


10 mm



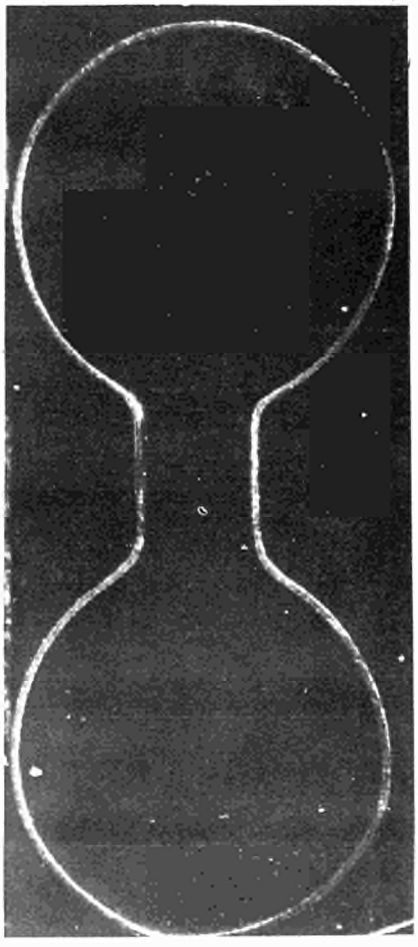
1 mm

lengthwise section of 2 mm pitch helically grooved tube



5 mm

cross-section of finned tube



cross-section of "figure eight" shaped tube

5 mm

Heat transfer and friction factor diagram for forced convection non-boiling-, subcooled boiling- and burn-out heat transfer of pure OM_2 in a vertical, round stainless steel tube of 5 mm inside diameter, 500 mm effective electrically heated length, 0.25 mm wall thickness, c.a.l. 0.8 μ surface roughness, at 2.9 bar static pressure at outlet and 417°C saturation temperature

Final Report 1965
Euratom Contract No 166-64-6 ORGN
Central Technical Institute T.N.O.
The Hague – Netherlands

friction factor, $f_h = \frac{\pi^2 D^5 \rho}{8 L \varphi_m^2} \Delta P$

(properties at average bulk temperature)

saturation temperature at outlet minus bulk temperature at outlet is degree of subcooling, Δt_{sub}

- $\Delta t_{sub} = 10^\circ C$
- $\Delta t_{sub} = 30^\circ C$
- $\Delta t_{sub} = 50^\circ C$
- $\Delta t_{sub} = 70^\circ C$

heat flux, Φ (W/cm^2)

wet-wall temperature at outlet minus bulk temperature at outlet, $t_w - t_b$ (°C)

burn-out limit

subcooled boiling region

non-boiling region

red curves : mass velocity = 0.05 kg/sec
blue curves : mass velocity = 0.1 kg/sec
black curves : mass velocity = 0.15 kg/sec
green curves : mass velocity = 0.2 kg/sec

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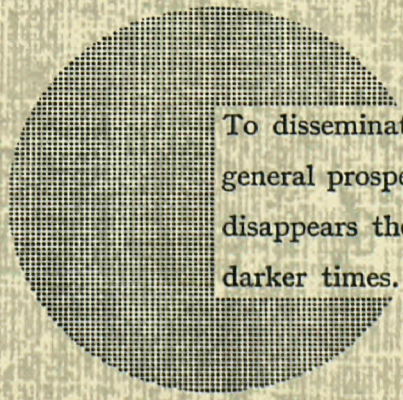

To disseminate knowledge is to disseminate prosperity -
general prosperity and not individual riches — and w
disappears the greater part of the evil which is
darker times.

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